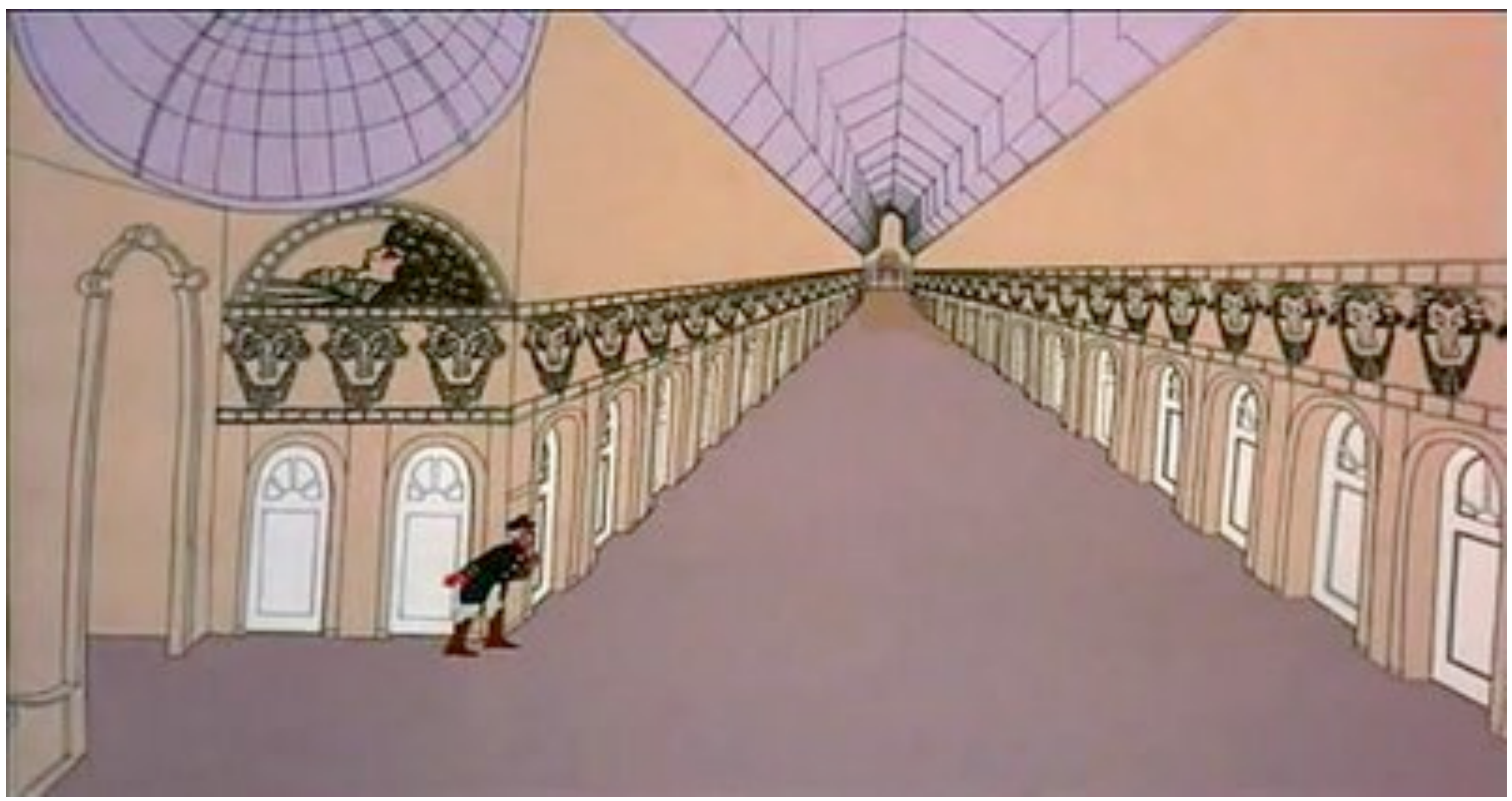
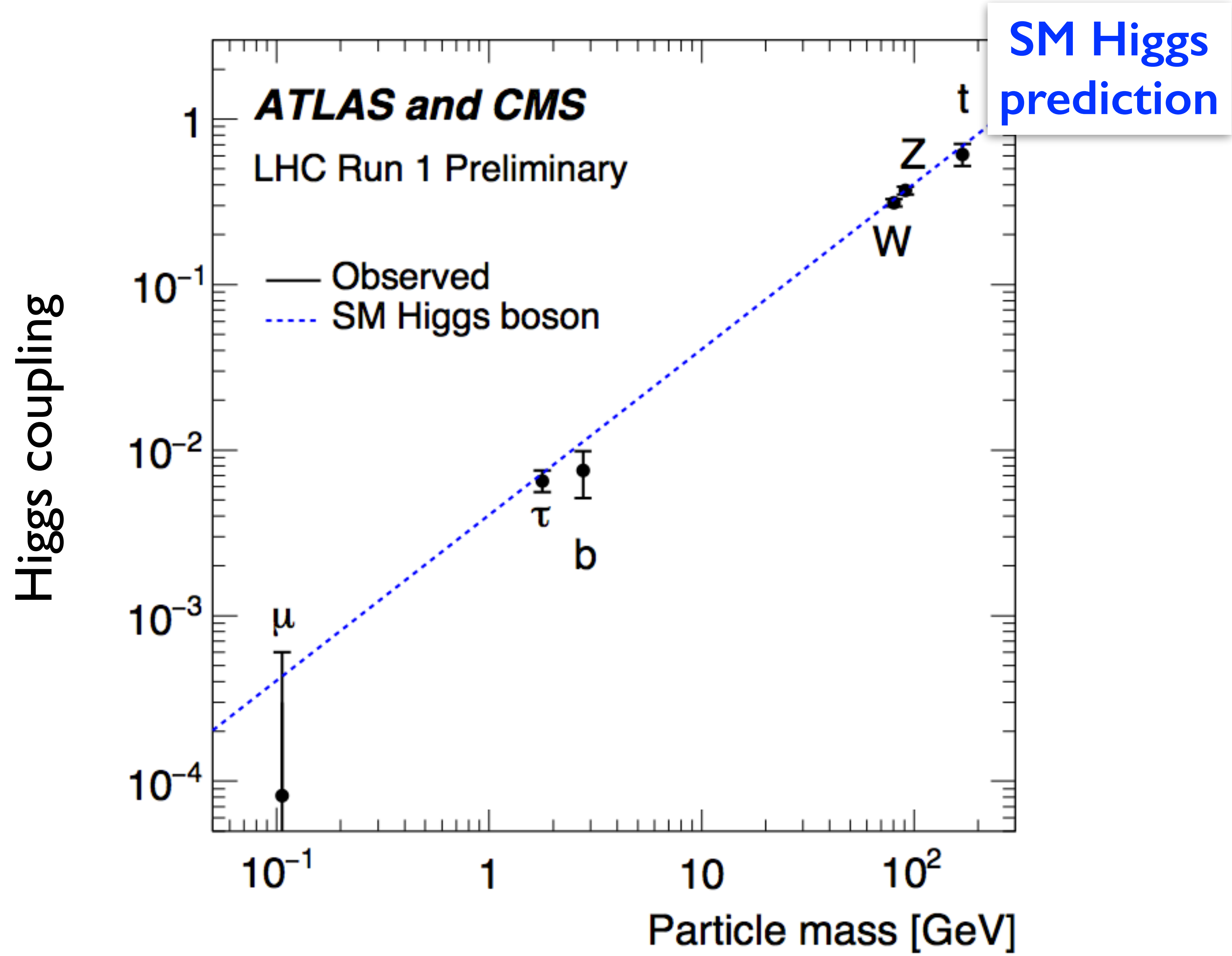
Searching for new paradigms after the Higgs



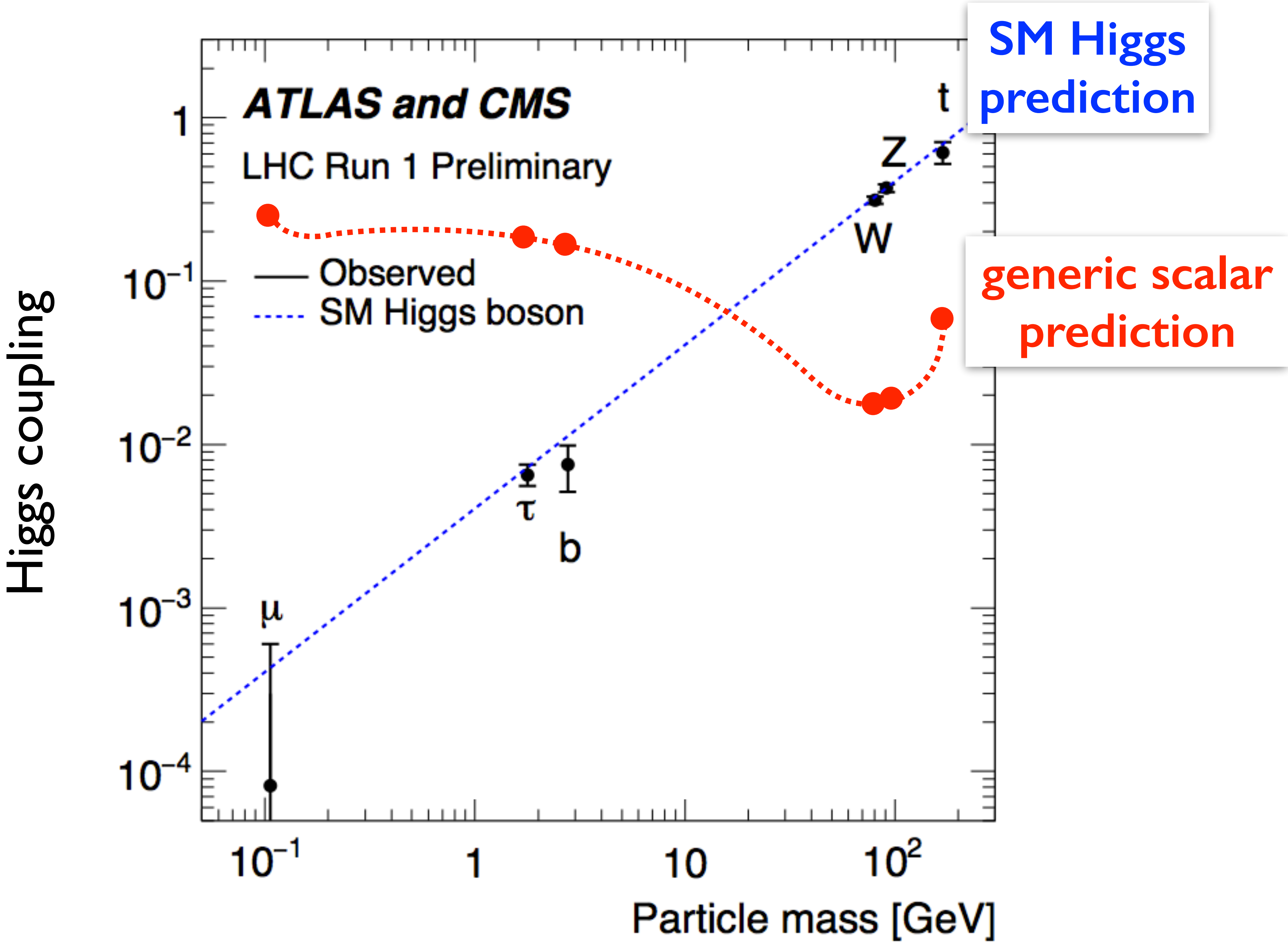
Alex Pomarol, CERN & UAB (Barcelona)

Best **LHC** Run I legacy: The Higgs discovery



Coupling-Mass relations as in the SM Higgs

Best **LHC** Run I legacy: **The Higgs discovery**



➥ **"Higgs impostors" left behind!**

The SM is established !

Where to expect new-physics (beyond the SM)?

Where a new paradigm is needed?

The SM is established !

Where to expect new-physics (beyond the SM)?

Where a new paradigm is needed?

To answer this, we can follow Einstein's path:

"*Gedankenexperiment*"

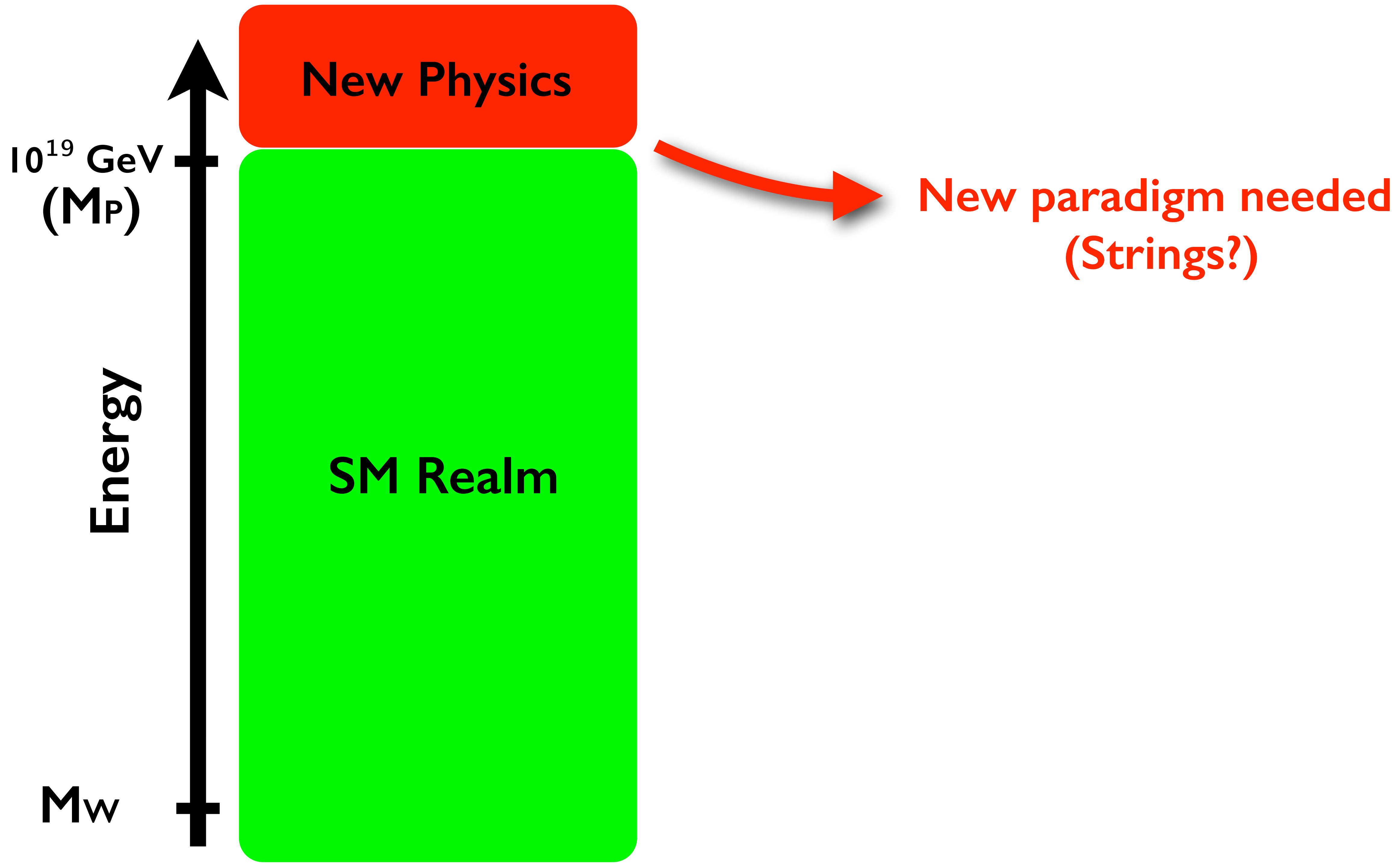
(*thought experiments*):

look at which regime the theory **fails,**
and therefore **new physics** must appear!

☛ <u>no-lose theorem</u>
for a discovery

guaranteed the discover of the positron, charm,…, top & Higgs (or something else)

With m_H~125 GeV, **the SM**, is a consistent theory all the way to M_P



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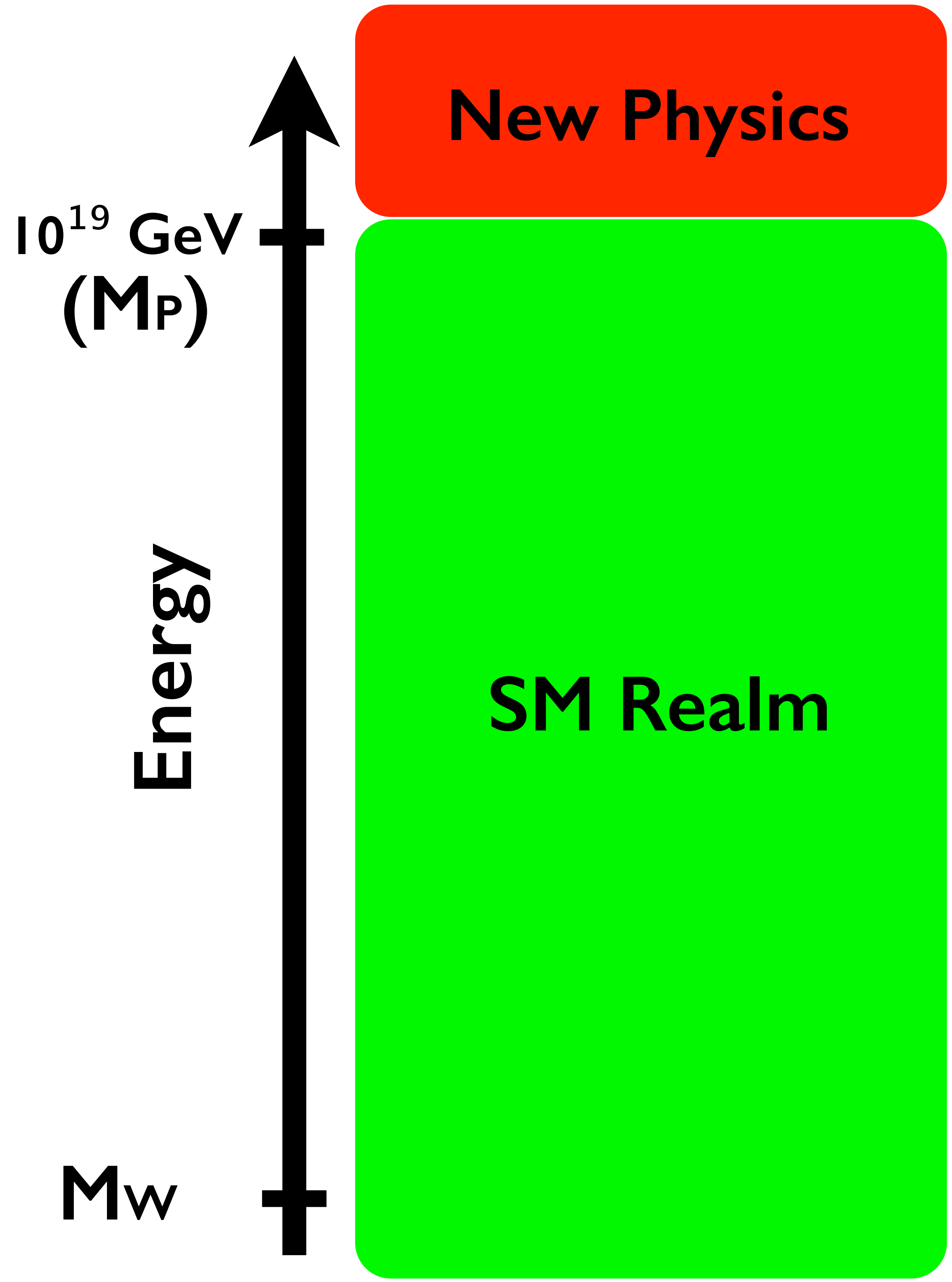
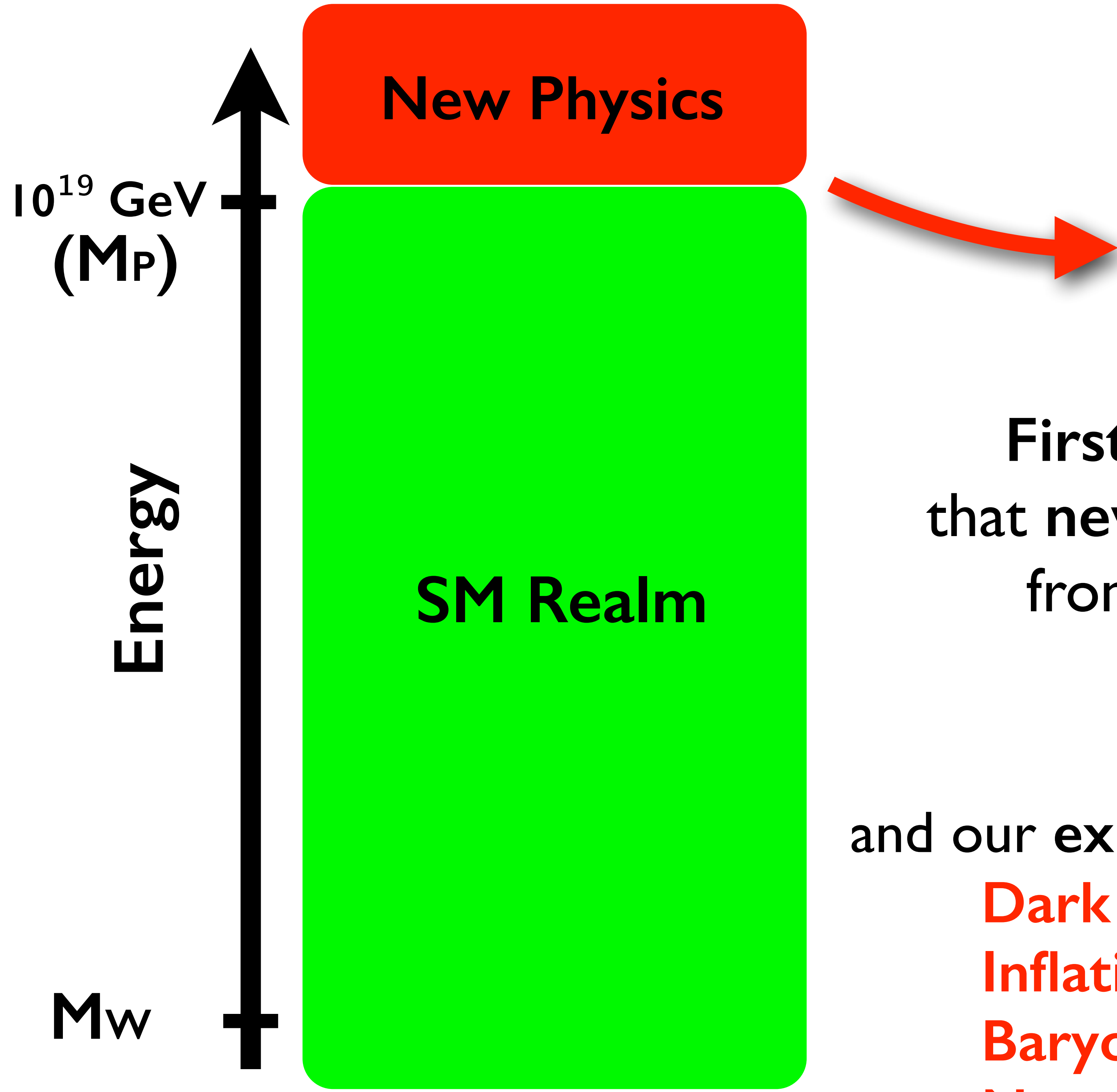


New paradigm needed
(Strings?)

First time in particle physics that **new-physics** scale is **far away** from current **experiments**

dying of success?

With $m_H \sim 125$ GeV, **the SM**, is a consistent theory all the way to M_P



New paradigm needed
(Strings?)

First time in particle physics
that **new-physics** scale is **far away**
from current **experiments**

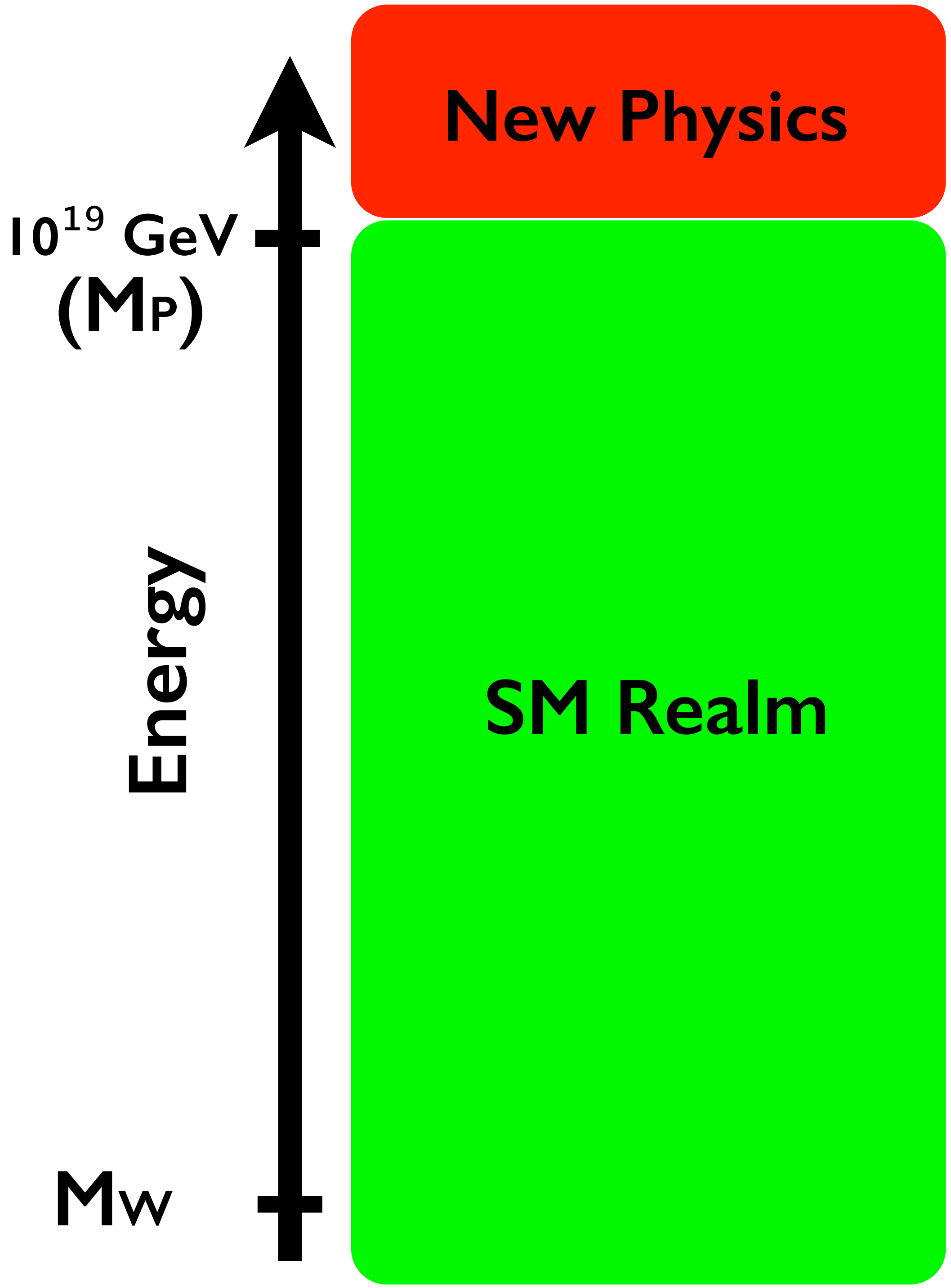
dying of success?

and our **experimental** evidence for BSM:

- Dark Matter
- Inflation
- Baryogenesis
- Neutrino masses

could well have their **origin** at that scale!

With m_H~125 GeV, **the SM**, is a consistent theory all the way to M_P



New motivation to go beyond:
Naturalness (Esthetics!)

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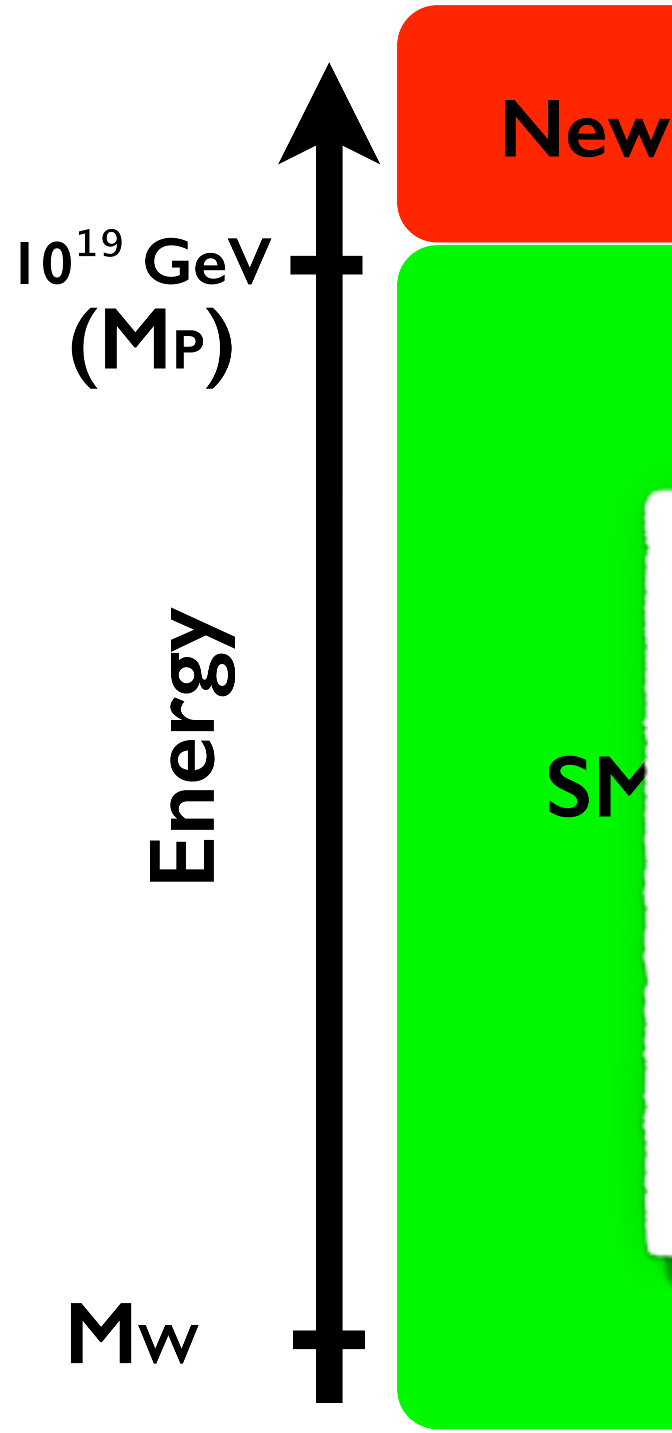

New motivation to go beyond:
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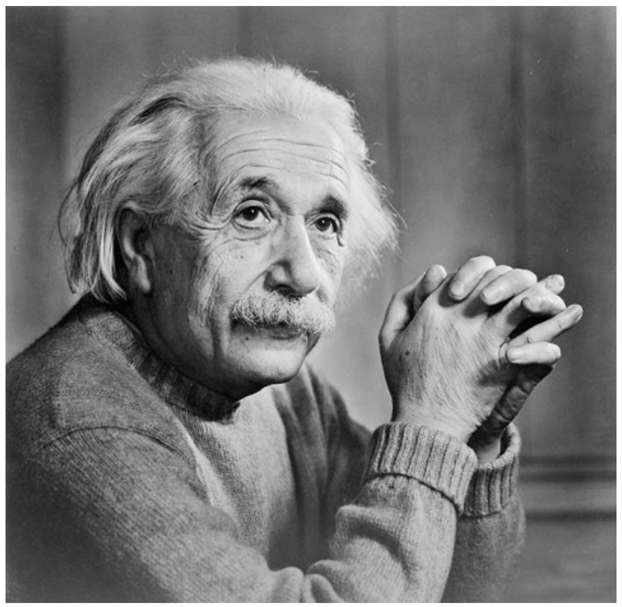
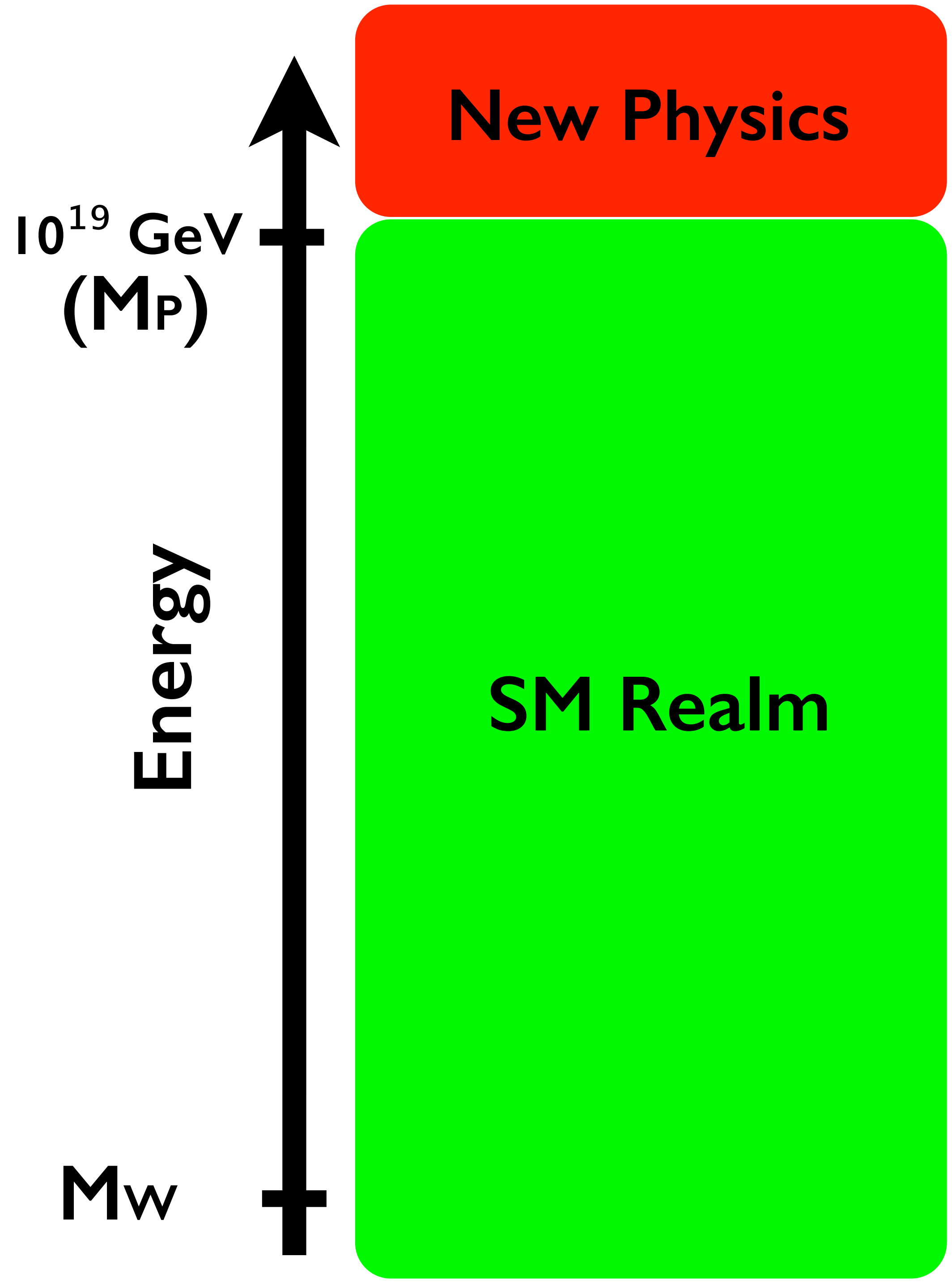
Following a more (risky) mature Einstein's path:



"the principle of the universe will be beautiful and simple"

With $m_H \sim 125$ GeV, **the SM**, is a consistent theory all the way to M_P



New motivation to go beyond:
Naturalness (Esthetics!)

m_H << M_P
Why so different?
Not natural/stable to expect

The Higgs-mass problem in a nutshell

	Massless	Massive	
Vector $\mathbf{A}_\mu$	2 *dof* (+,-)	3 *dof* (+,0,-)	*2≠3 ✔ Massless vectors are save*
Fermion Ψ	2 *dof* Ψ_L	4 *dof* Ψ_L , Ψ_R	*2≠4 ✔ Massless fermions are save*
Scalar $\mathbf{h}$	1 *dof*	1 *dof*	*1=1 Problem!*

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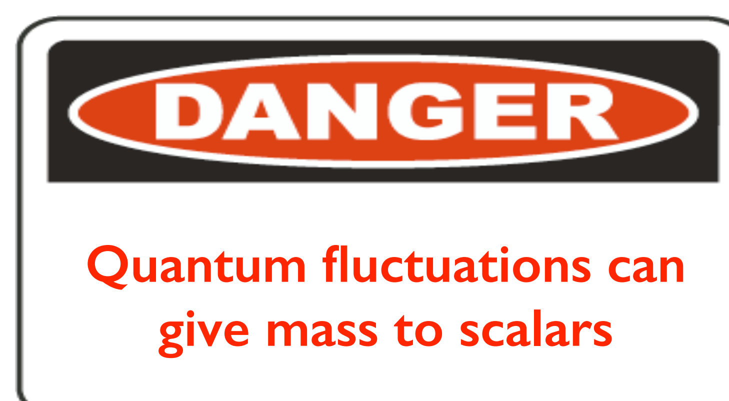
2≠4 ✔ *Massless fermions are save*

1=1 Problem!



$m_H << M_P$?

Towards a new paradigm

"fermionizing"
the Higgs

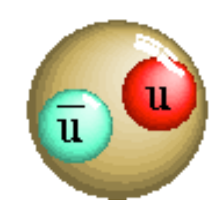
Supersymmetry

"Marrying" a fermion:

Higss $\longleftrightarrow$ Higgsino

Compositeness

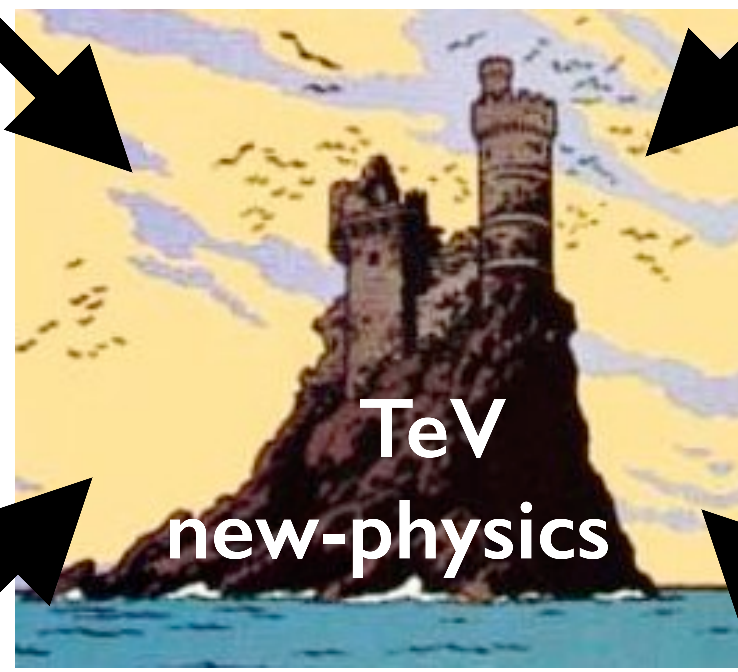
The "transvestite" Higgs:

H = 

Attacking the new paradigm from several fronts

Looking for
deviations in **Z/W** couplings
& new particles
LEP/Tevatron

Looking for
new **flavor**-transitions



Looking for
deviations in **Higgs** couplings
& new particles

Looking for
Electric Dipole Moments

No Success so far!

First main weapon to attack physics **Beyond the SM** (BSM):

LEP

~ millions of Z produced

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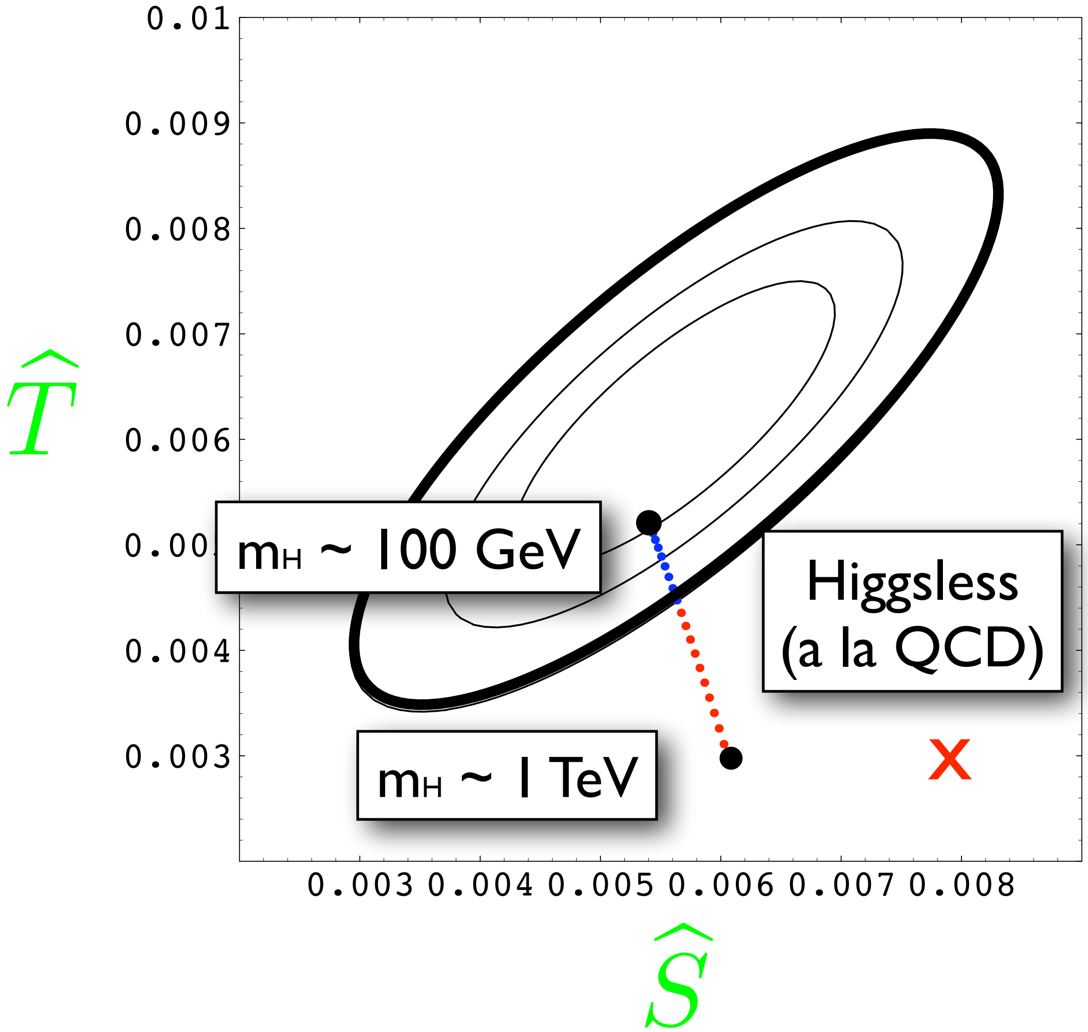

Deviations were **expected**
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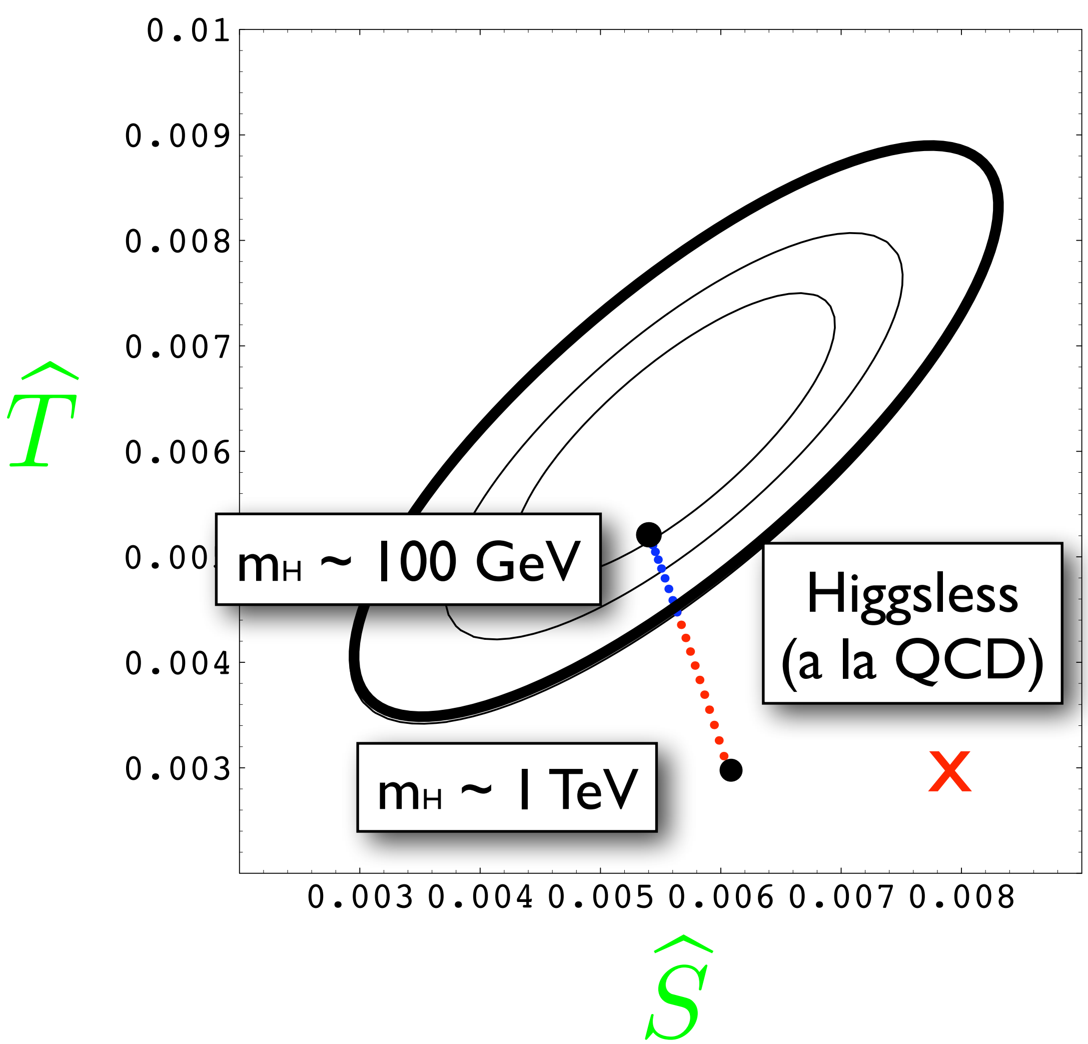

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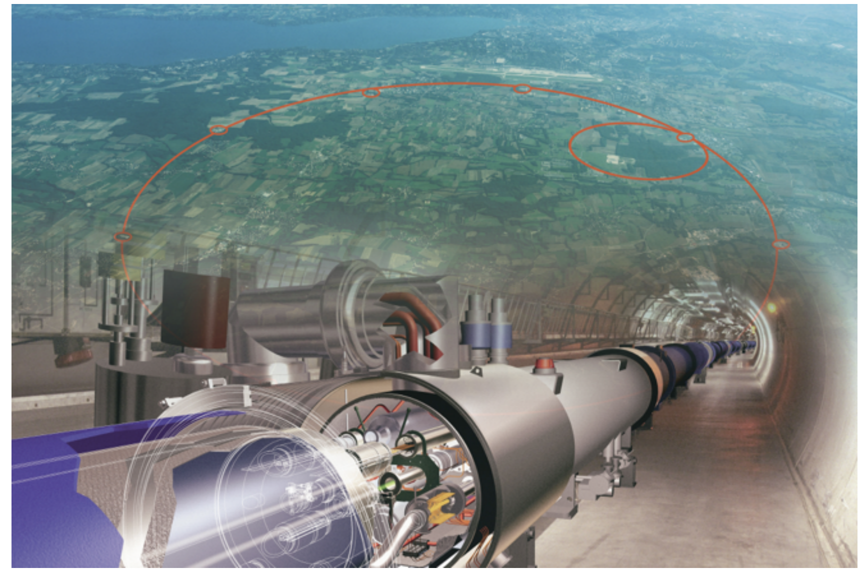
Bad luck?

We built a more powerful weapon:

LHC



It has brought an important new discovery: **The Higgs !**

crucial new "handle" to catch BSMs:

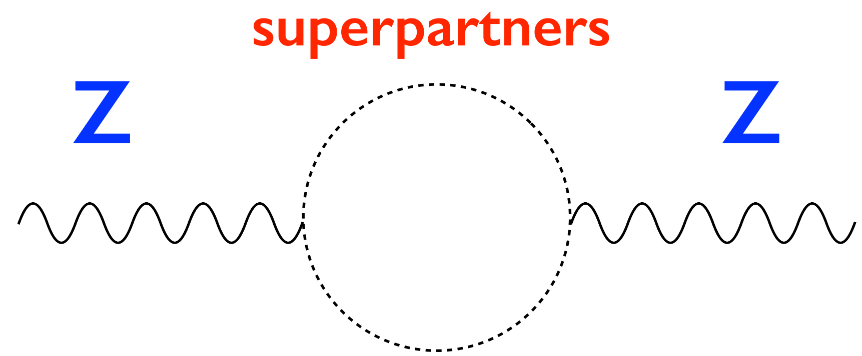
With the **Higgs**, we have had access to
new relevant information by measuring its **properties**

The Higgs is the most "sensitive"
SM particle to new-physics,
and therefore
the <u>best place to look for *natural* BSM</u>

Examples:

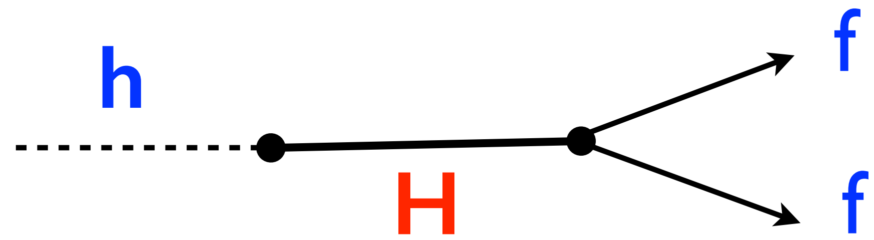
1) MSSM:

Gauge bosons:



~ loop effects

Higgs:



~ tree-level effects

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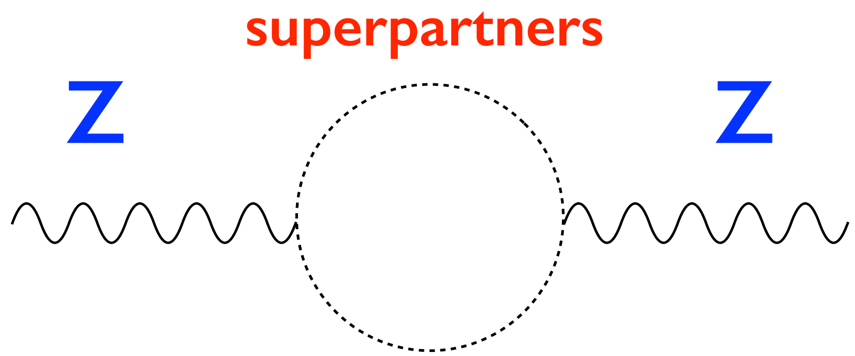

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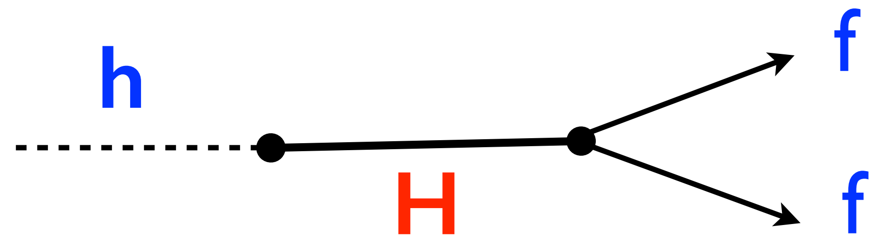

~ tree-level effects

☛ Effects in Higgs physics can be a factor $16\pi^2 \sim 100$ larger!

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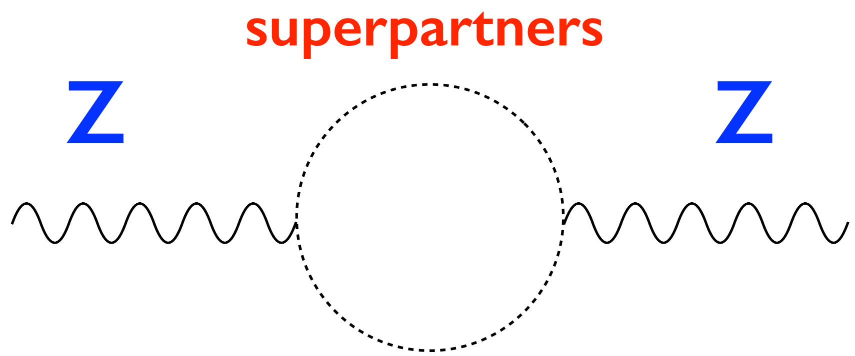

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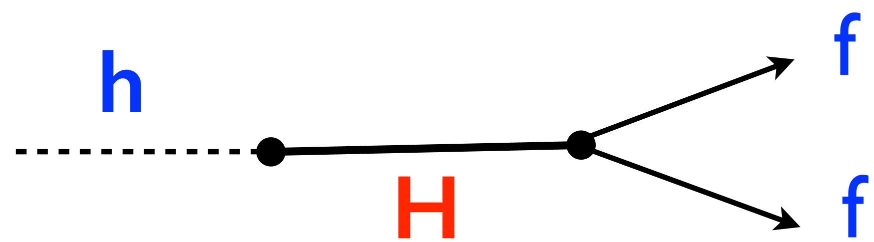
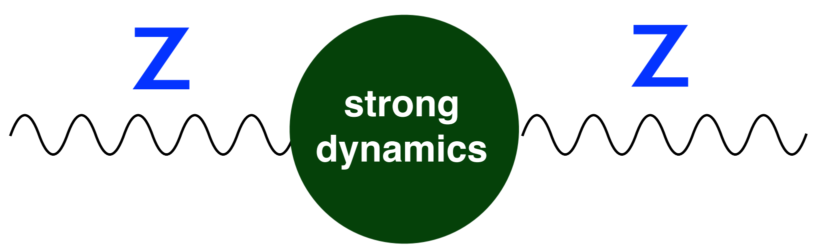


~ tree-level effects

Effects in Higgs physics can be a factor $16\pi^2 \sim 100$ larger!

2) Composite models:

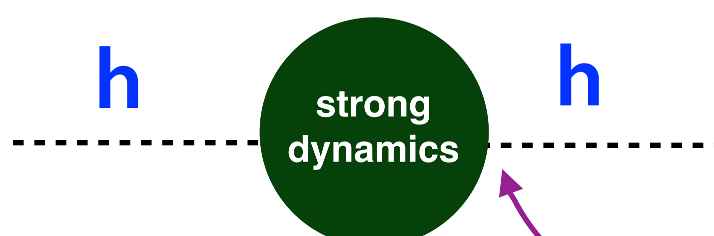
Gauge bosons:



$$\sim \frac{g^2 v^2}{\Lambda^2}$$

(Λ=composite scale)

Higgs:



$$\sim \frac{g_H^2 v^2}{\Lambda^2} \sim \frac{16\pi^2 v^2}{\Lambda^2}$$

"strong" Higgs coupling

Consequences:

➥ Even with less statistics at the **LHC**, similar impact today in new-physics as **LEP**

LEP: **ee$\to$ Z ($\to$ff) ~ millions of events**

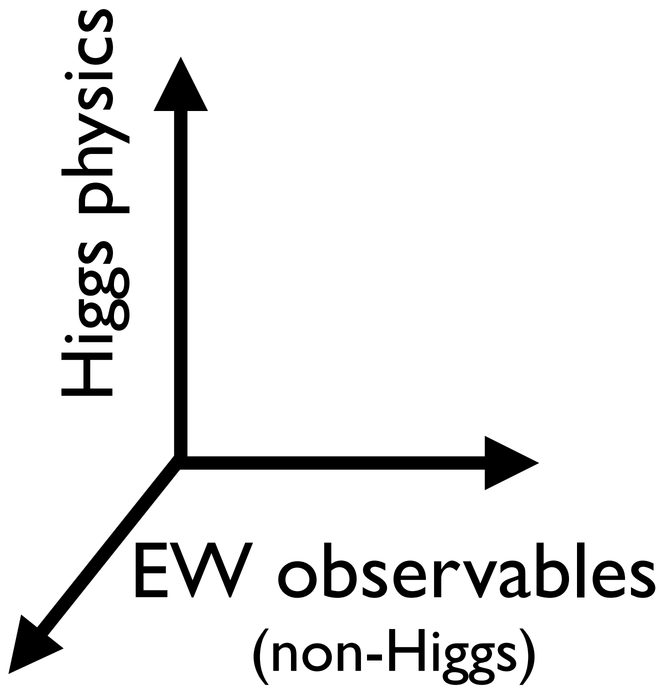
LHC: **pp$\to$h ($\to\gamma\gamma$) ~ thousands of events**

First question to address in Higgs couplings:

Which are the most relevant Higgs couplings to measure?

probes testing
new directions in the
"parameter space" of BSMs

Couplings that can be modified
by new-physics,
not affecting anything else



Assuming new-physics scale is heavier than m_H:

8 Primary Higgs couplings

(for CP-conservation and one family)

Elias-Miro, Espinosa, Masso, AP, JHEP 1311 (2013) 066
AP, Riva, JHEP 1401 (2014) 151

$$
\begin{aligned}
\Delta\mathcal{L}_{\rm BSM} = \quad & \delta g_{hff}\, h \bar{f}_L f_R + h.c. \qquad \text{(f=b, } \tau\text{, t)} \\
& + g_{hVV}\, h \left[W^{+\,\mu} W^-_\mu + \frac{1}{2\cos^2\theta_W} Z^\mu Z_\mu \right] \\
& + \kappa_{GG} \frac{h}{v} G^{\mu\nu} G_{\mu\nu} \\
& + \kappa_{\gamma\gamma} \frac{h}{v} F^{\gamma\,\mu\nu} F^\gamma_{\mu\nu} \\
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Corresponds to the 8 possible dim-6 operators with $|H|^2$:

$$|H|^2\bar f_L H f_R + h.c.$$
$$|H|^2|D_\mu H|^2$$
$$|H|^2 G^A_{\mu\nu}G^{A\mu\nu}$$
$$|H|^2 B_{\mu\nu}B^{\mu\nu}$$
$$|H|^2 W^a_{\mu\nu}W^{\mu\nu\,a}$$
$$|H|^6$$

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important:
custodial invariant!!
& zero-momentum

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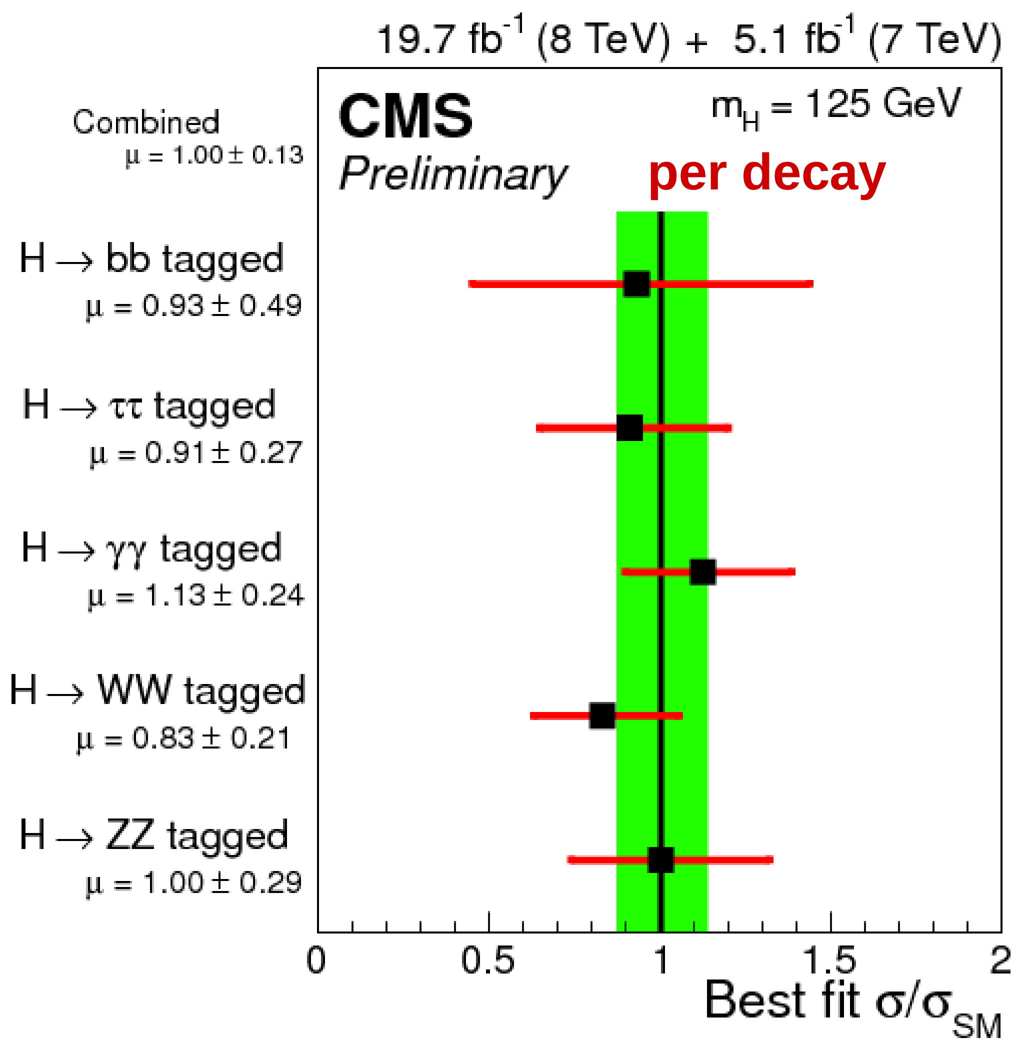
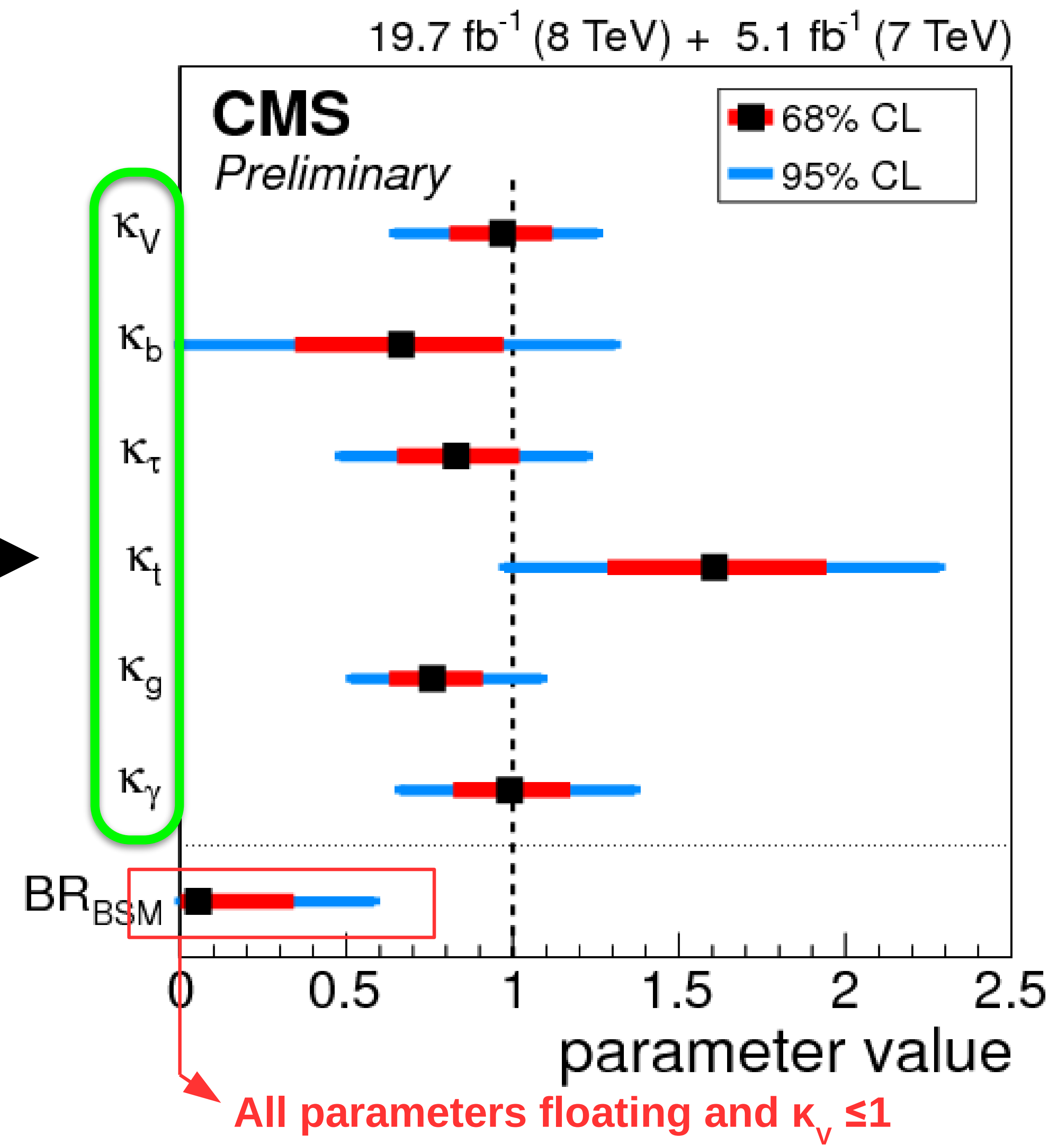
6 measured at the LHC
(the "kappas")

Higgs coupling determination

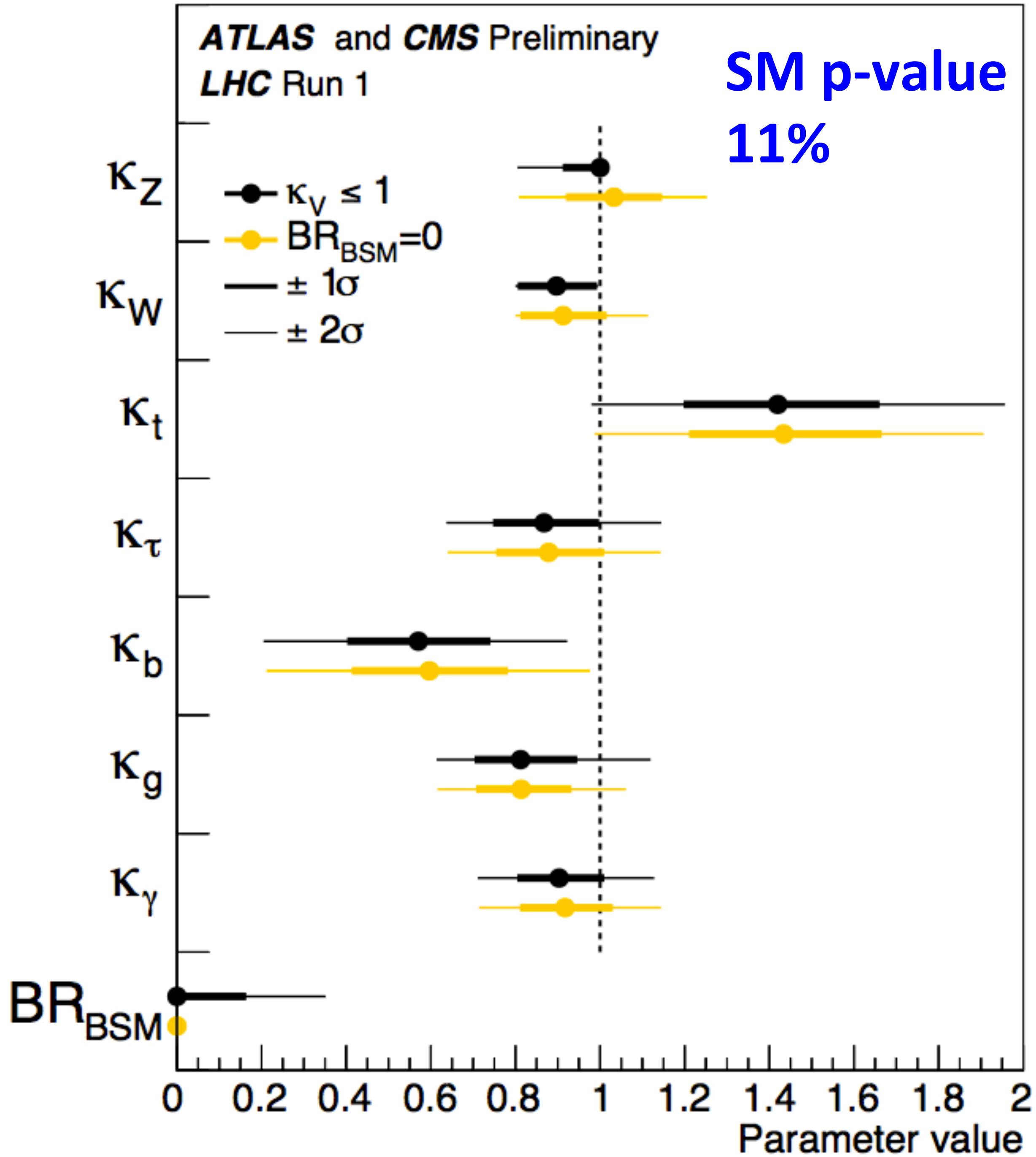


$$\kappa_i = \frac{g_{hii}}{g_{hii}^{\mathrm{SM}}}$$



reasonable good agreement with the SM !

Combined analysis:



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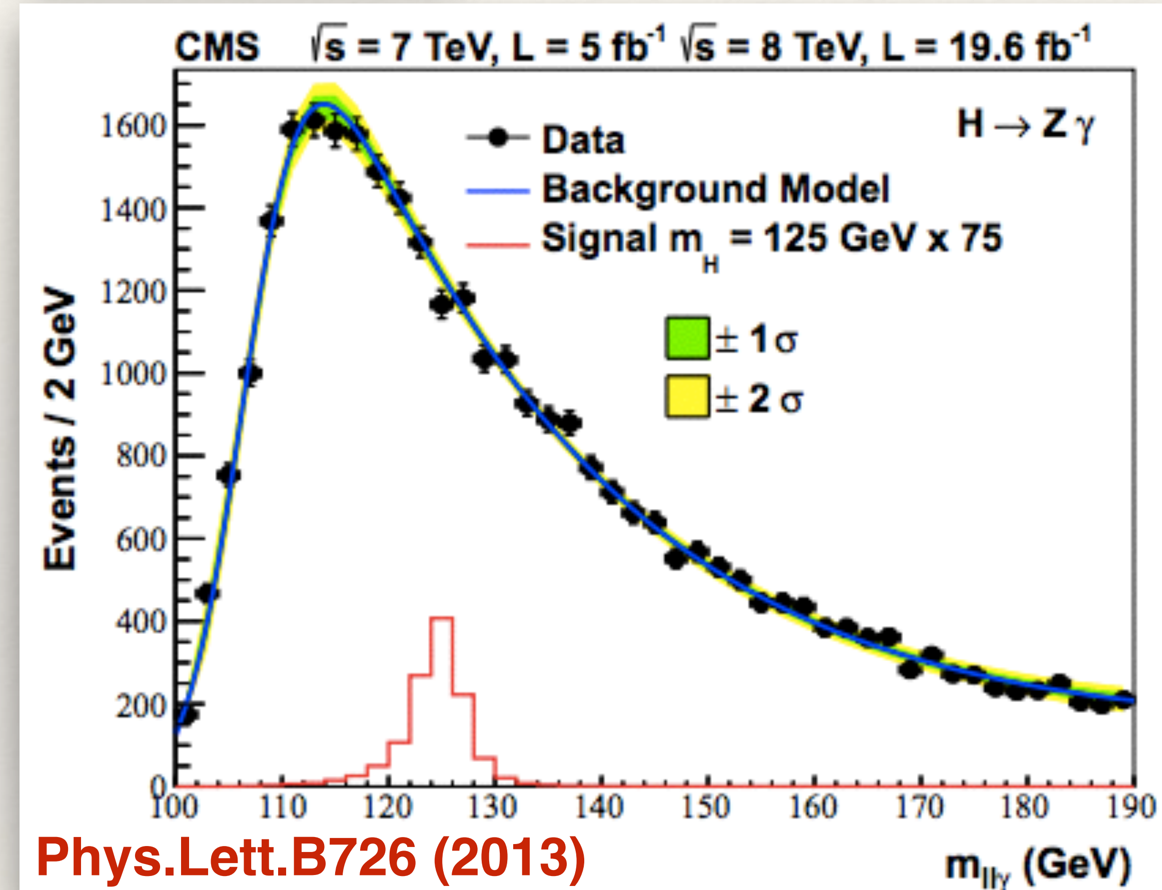
6 measured at the LHC (the "kappas")

2 still to be measured

$h \to Z\gamma$

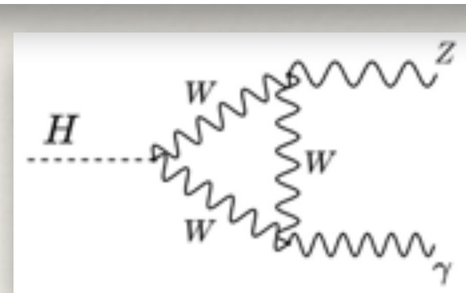
It can be measured in the far future by $GG \to hh$

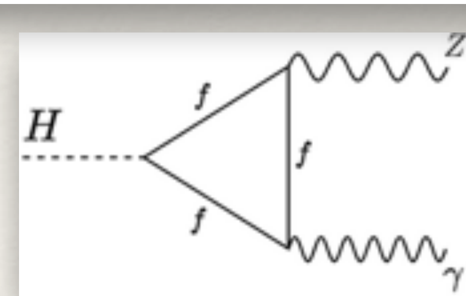
Experimental bound on h→Zγ



CMS ($H \to Z\gamma$): $\mu < 9$ (9 expected) at 95% CL

BR(h→Zγ)~0.001 small in the SM since it comes at one-loop:



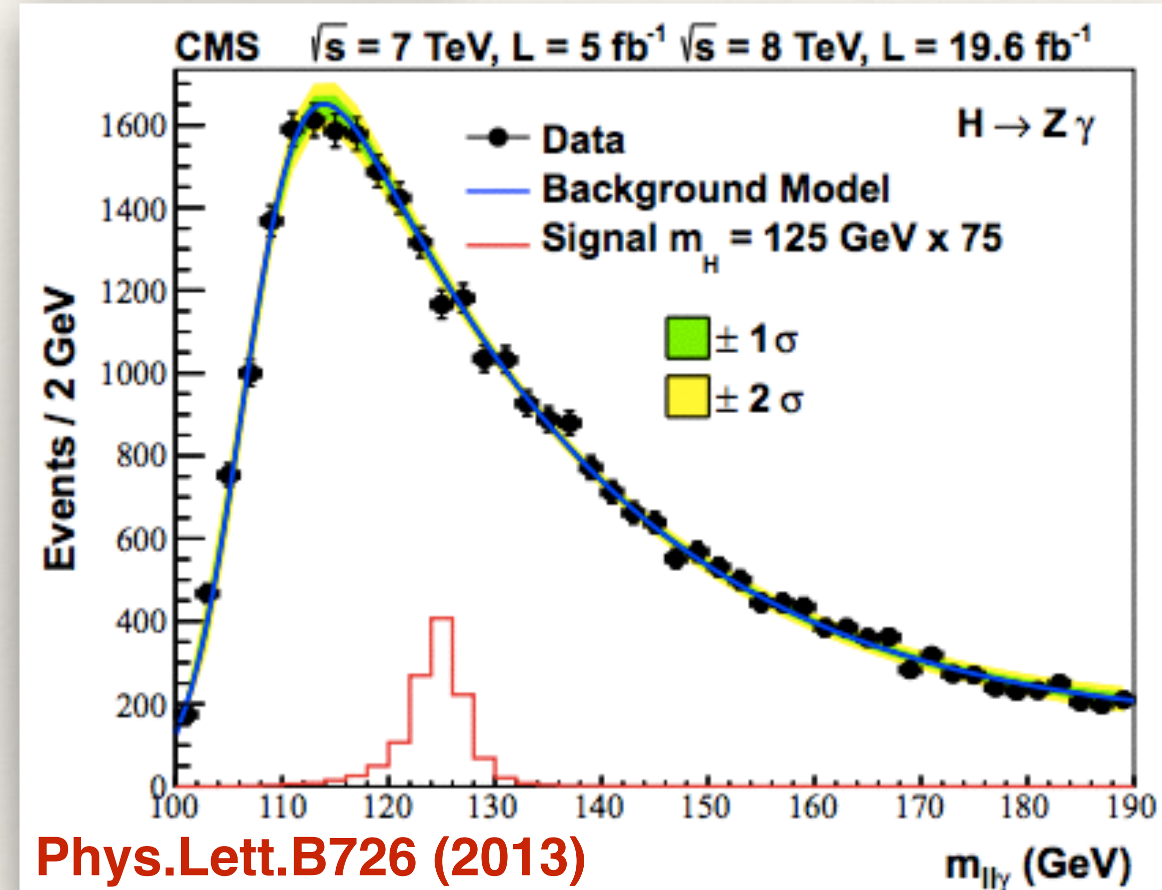


still allowed to be 9 x BR_{SM}

... last hope for finding O(1) deviations?

(possibility in **composite Higgs** models)

Experimental bound on h→Zγ



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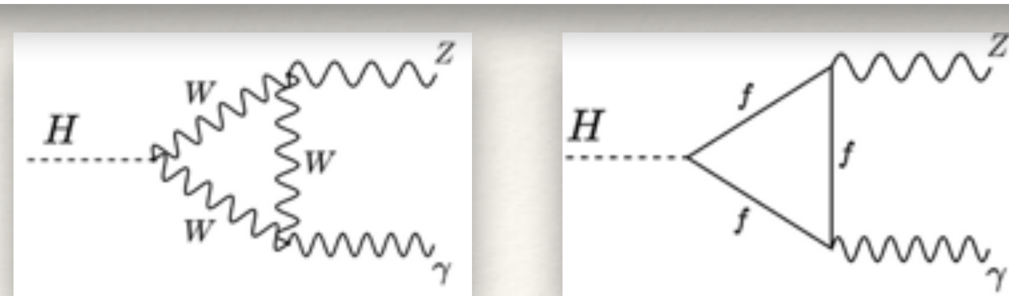

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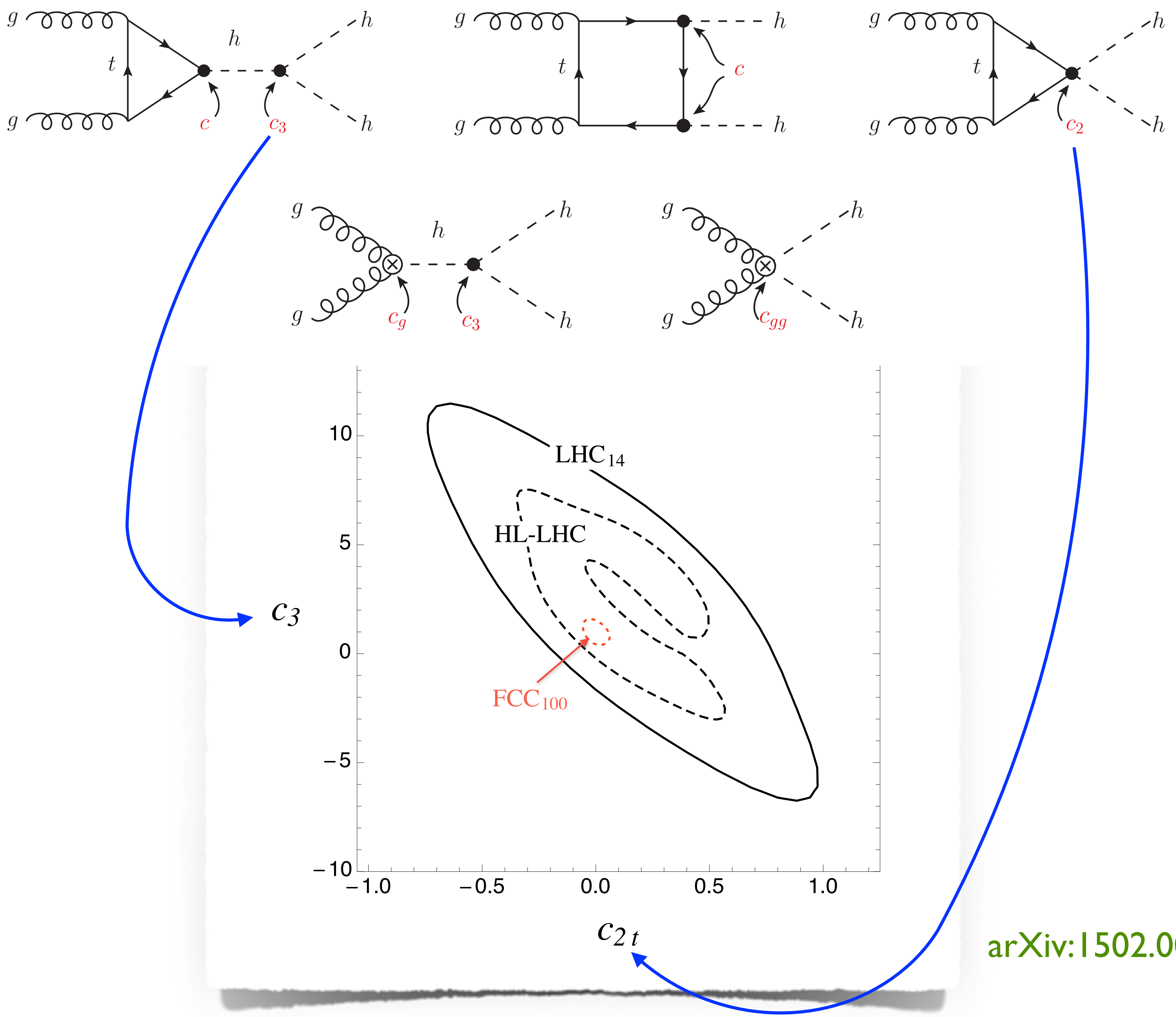
Prospects for 3h-coupling



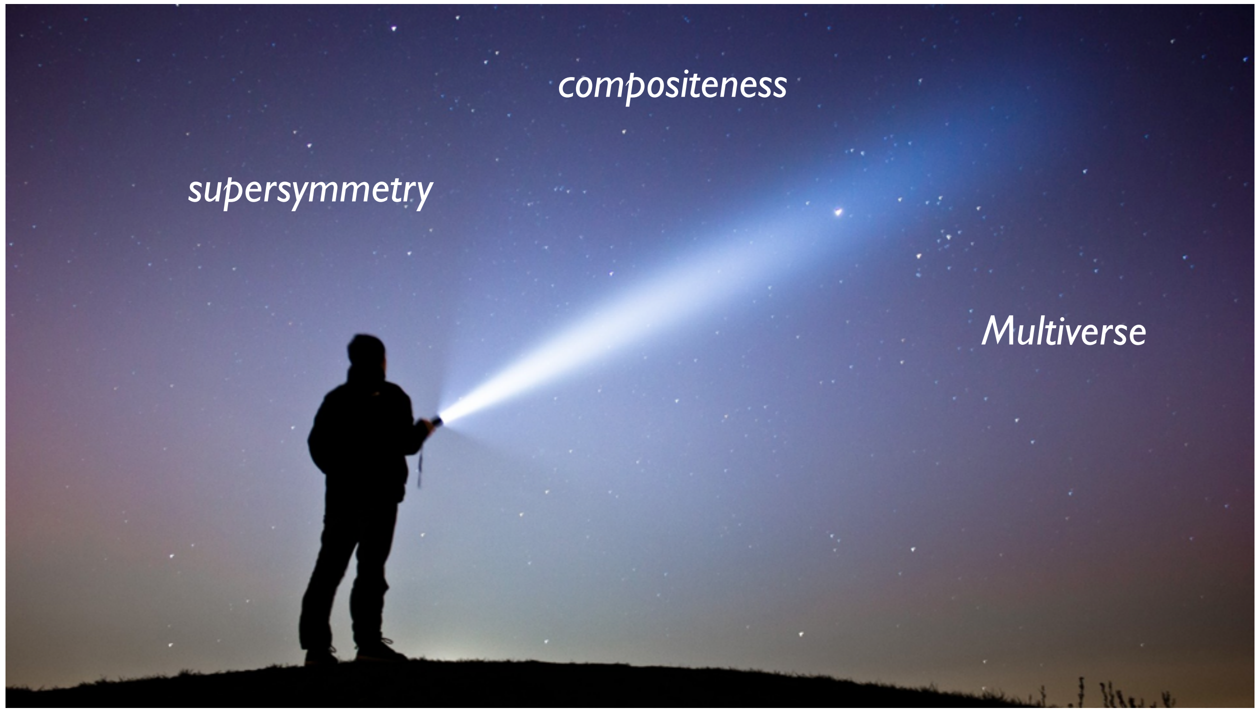
arXiv:1502.00539

Impact on BSM from Higgs coupling measurements

- Today, as Higgs coupling measurements agree with the SM, we only place bounds on new-physics

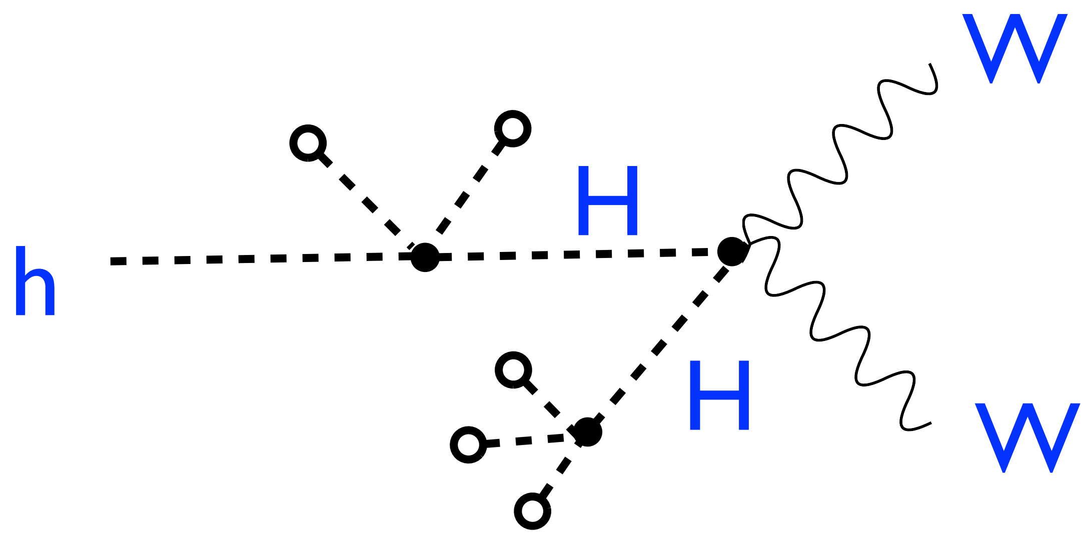
  The Higgs is our best weapon of BSM mass-destruction

- Tomorrow, who knows, it can illuminate on new-physics

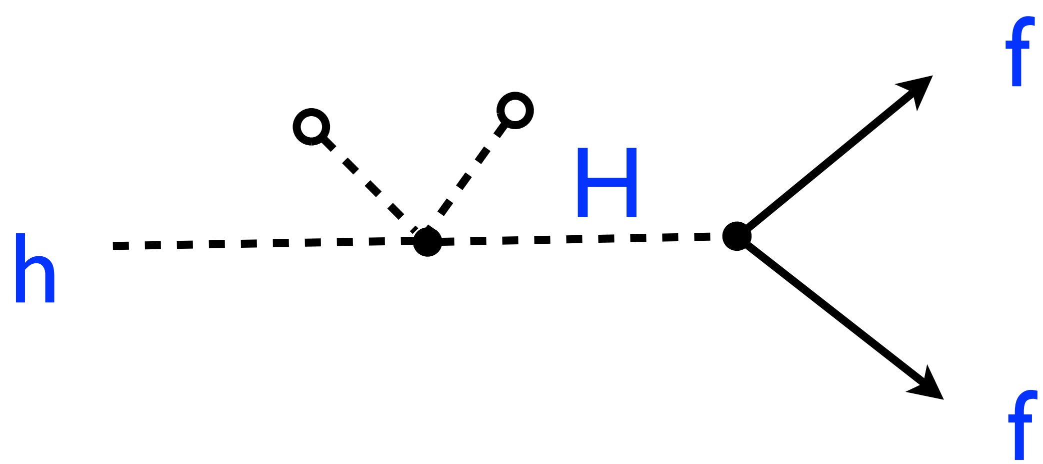


MSSM with heavy spectrum (≫100 GeV)

Main effects from the **2nd Higgs doublet:**



$$\sim \frac{v^4}{M_H^4}\, v^2$$



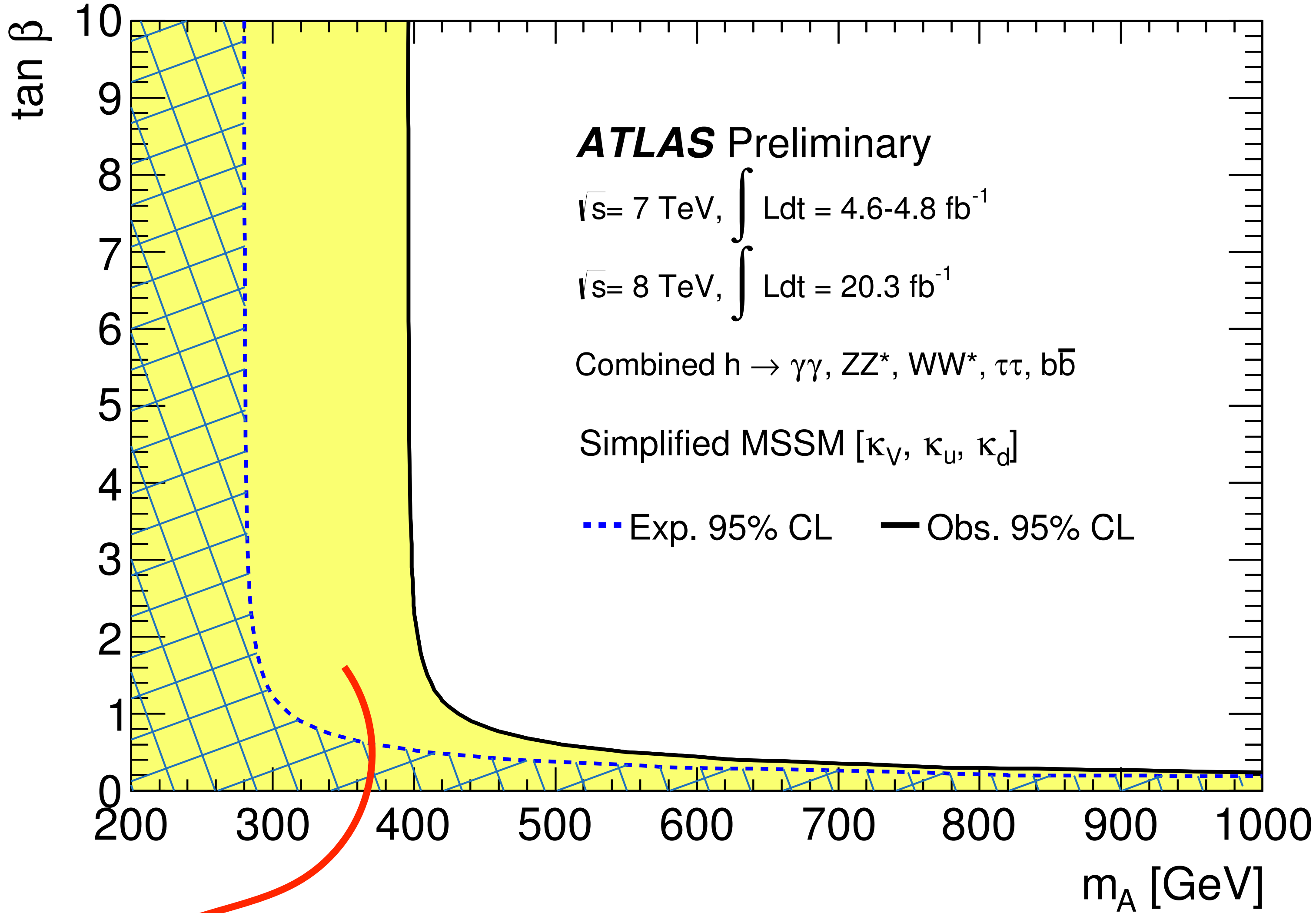
$$\sim \frac{v^2}{M_H^2}$$

Dominant effect!

Superpartners can only modify Higgs couplings at the loop-level:
Only stops/sbottoms give some contribution to hgg/hγγ (not very large)

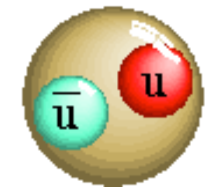
Supersymmetric Models (MSSM)

Higgs coupling measurements already
rules out susy-parameter space



not yet possible by direct searches

Composite Higgs

H = 

(Higgs as a pion)

Couplings dictated by symmetries (as in the QCD chiral Lagrangian)

$$\frac{g_{hWW}}{g_{hWW}^{\mathrm{SM}}}=\sqrt{1-\frac{v^2}{f^2}}$$

Giudice,Grojean,AP,Rattazzi 07

f = Decay-constant of the PGB Higgs related to the compositeness scale

(model dependent but expected f ~ v)

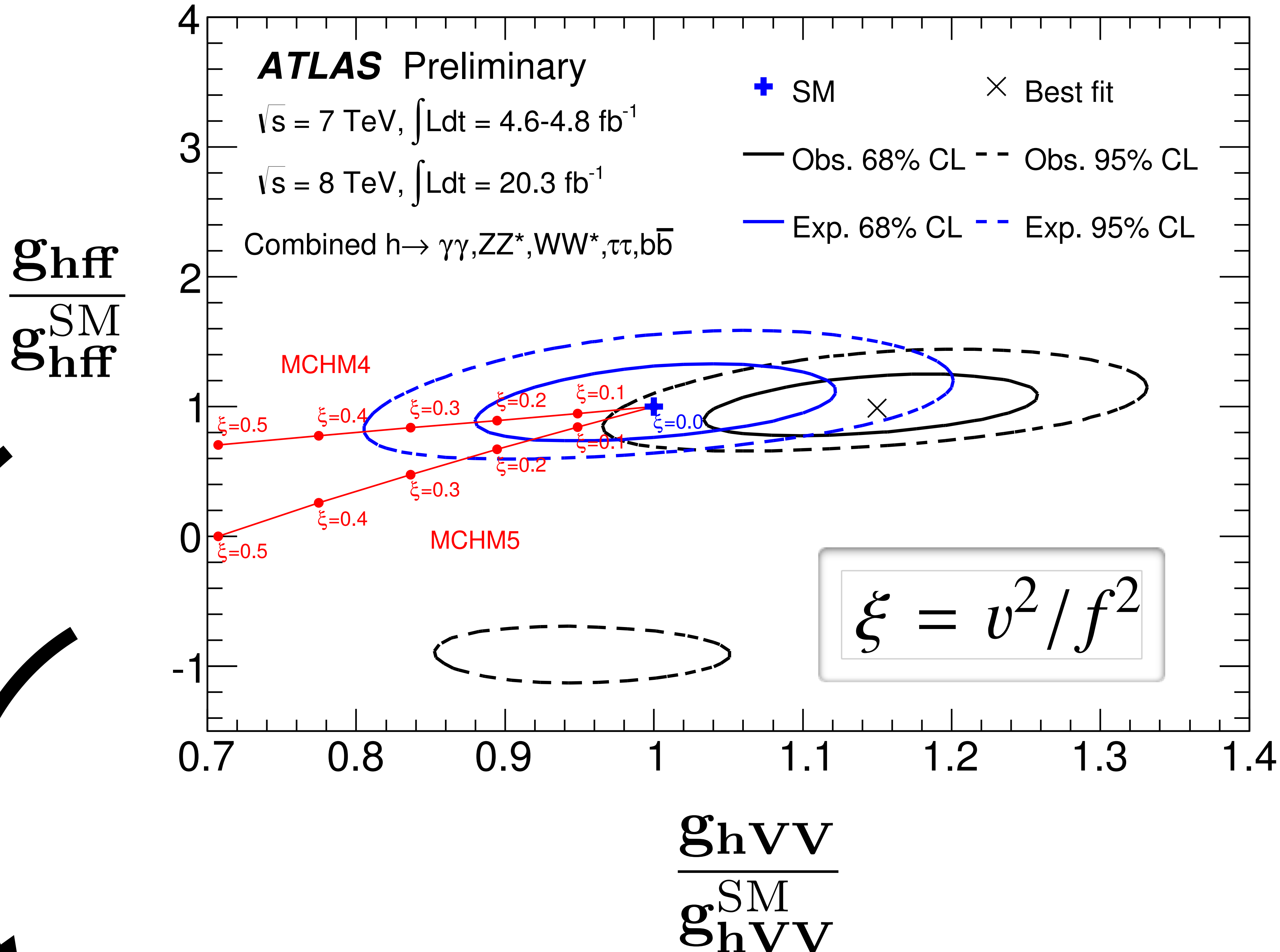
AP,Riva 12

$$\frac{g_{hff}}{g_{hff}^{\mathrm{SM}}}=\frac{1-(1+n)\frac{v^2}{f^2}}{\sqrt{1-\frac{v^2}{f^2}}}$$

$$n=0,1,2,\ldots$$

MCHM4 **MCHM5**

small deviations on the h$\gamma\gamma$(gg)-coupling due to the Goldstone nature of the Higgs



observed (expected) 95% CL upper limit of $\xi < 0.12$ (0.29) **MCHM4**

$\xi < 0.15$ (0.20) **MCHM5**

New Higgs decays also possible

The most interesting one:

1) invisible Higgs decay:

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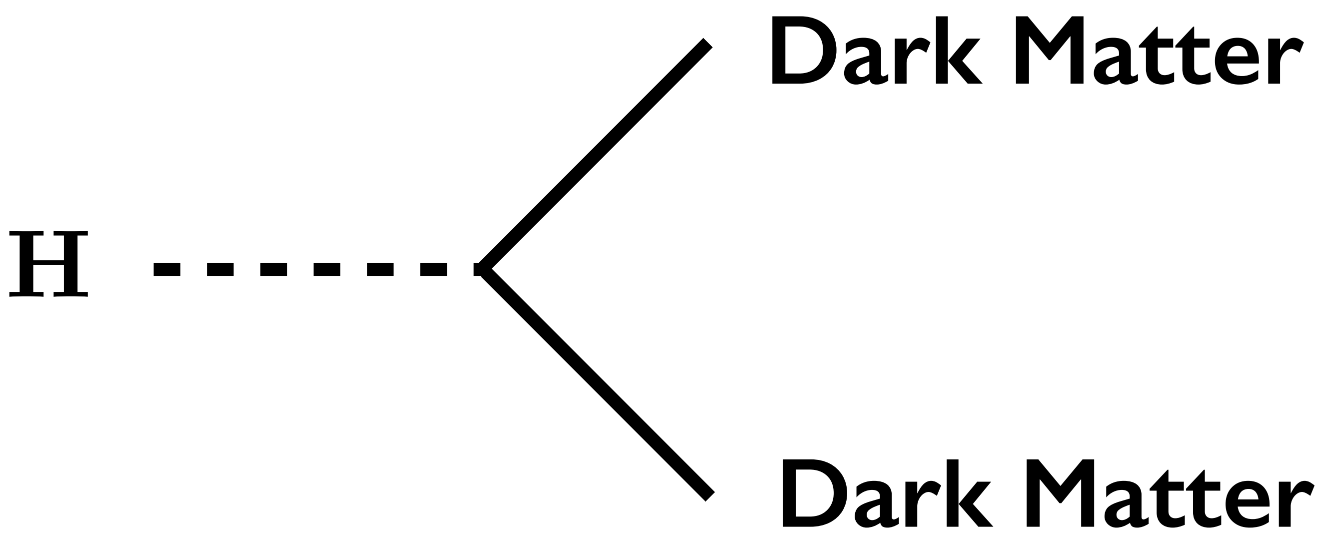

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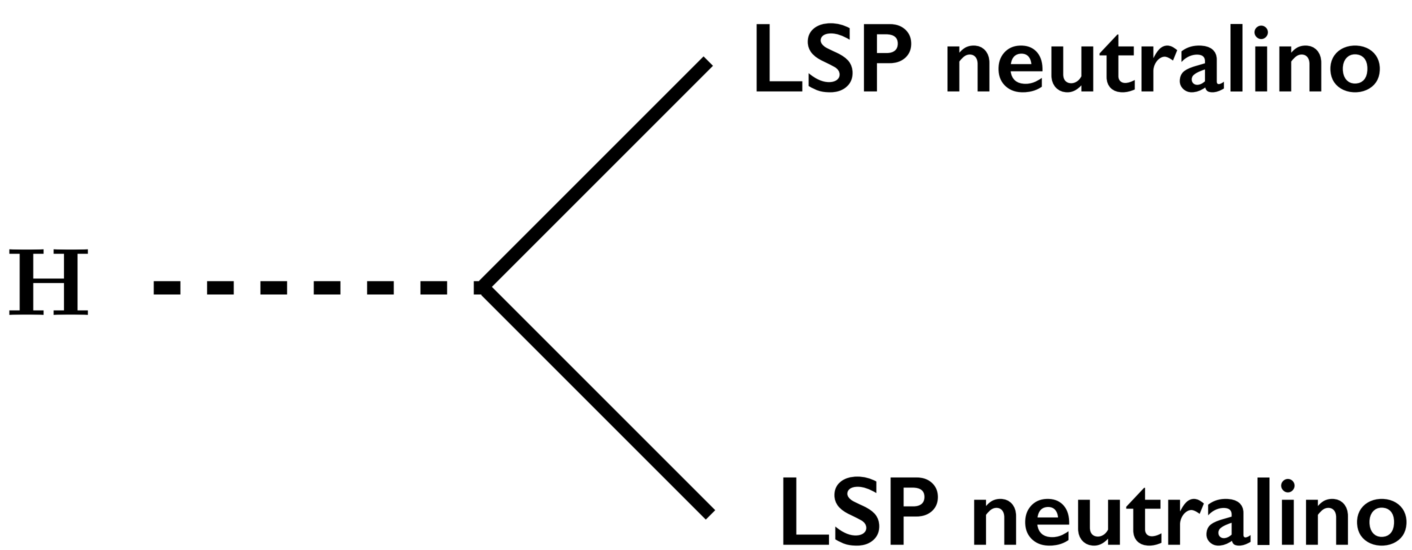

in supersymmetric models

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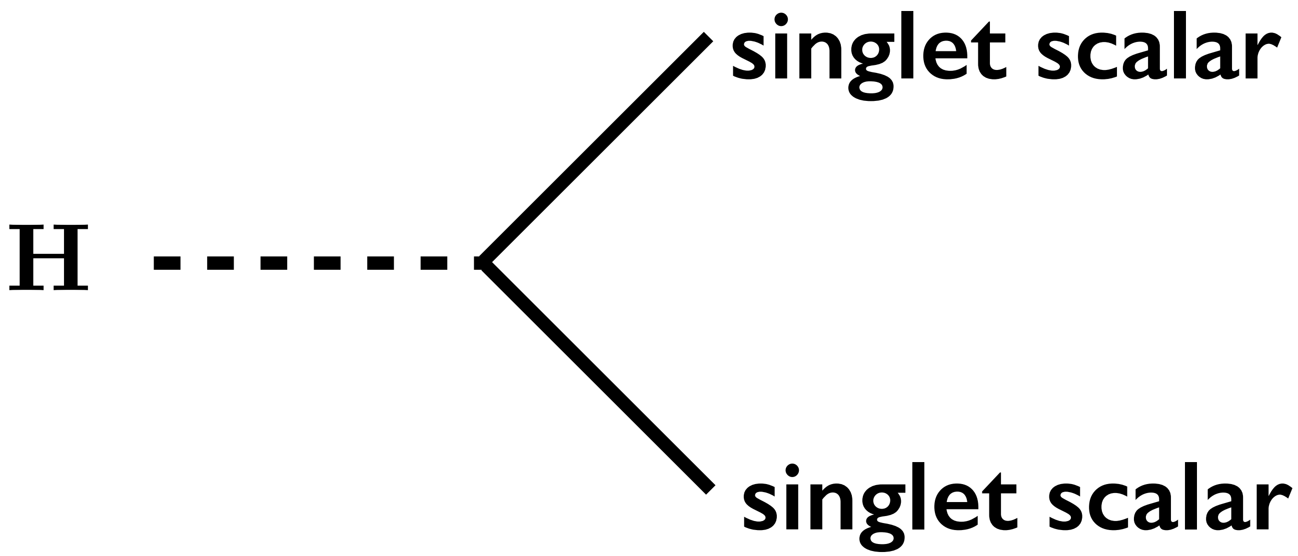

in models with more composite Higgs

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The most interesting one:

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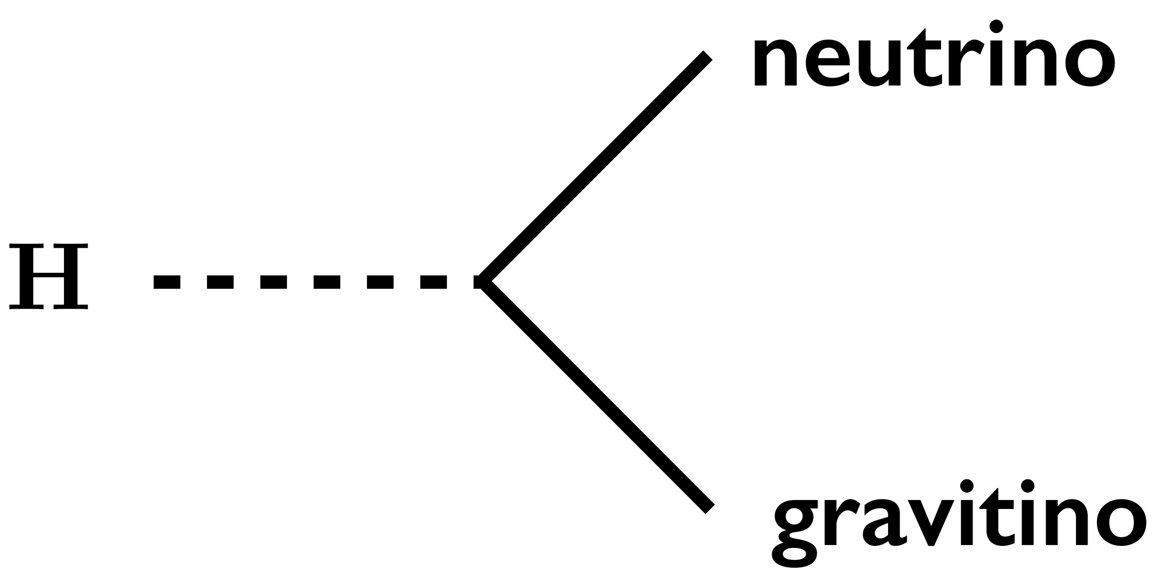
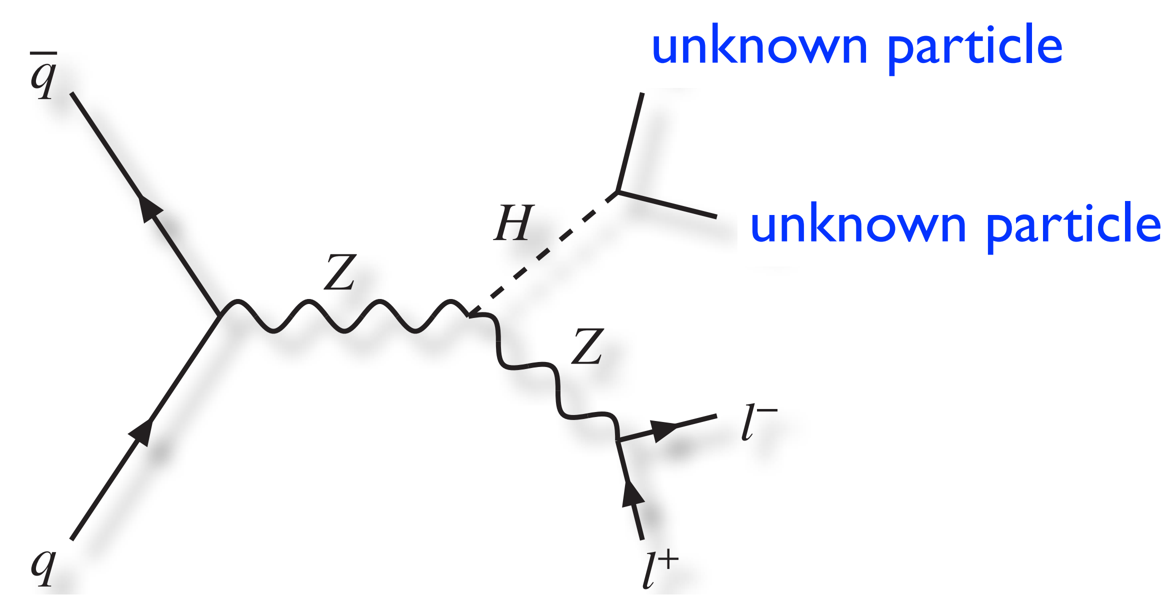


in theories where the Higgs
is the superpartner of the neutrino
Fayet,'76; AP,Riva,Biggio'12

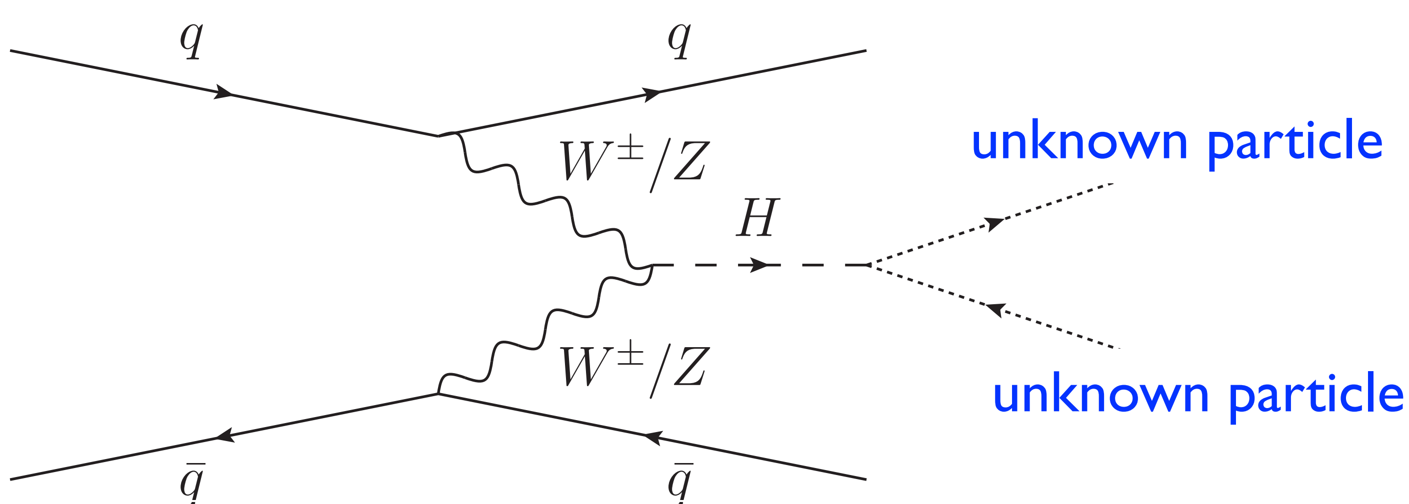
How to “see” it?

HV channel:



missing E_T + l^+l^-

VBF channel:



missing E_T + jets

No sign of so, up to now:

CMS: BR_{inv} < 58% (44% expected)

ATLAS: BR_{inv} < 29% (35% expected)

The **LHC** is a **discovery machine**,
and the search for new particles is the best option
for discovering new physics beyond the SM
(Higgs coupling measurements can only be complementary)

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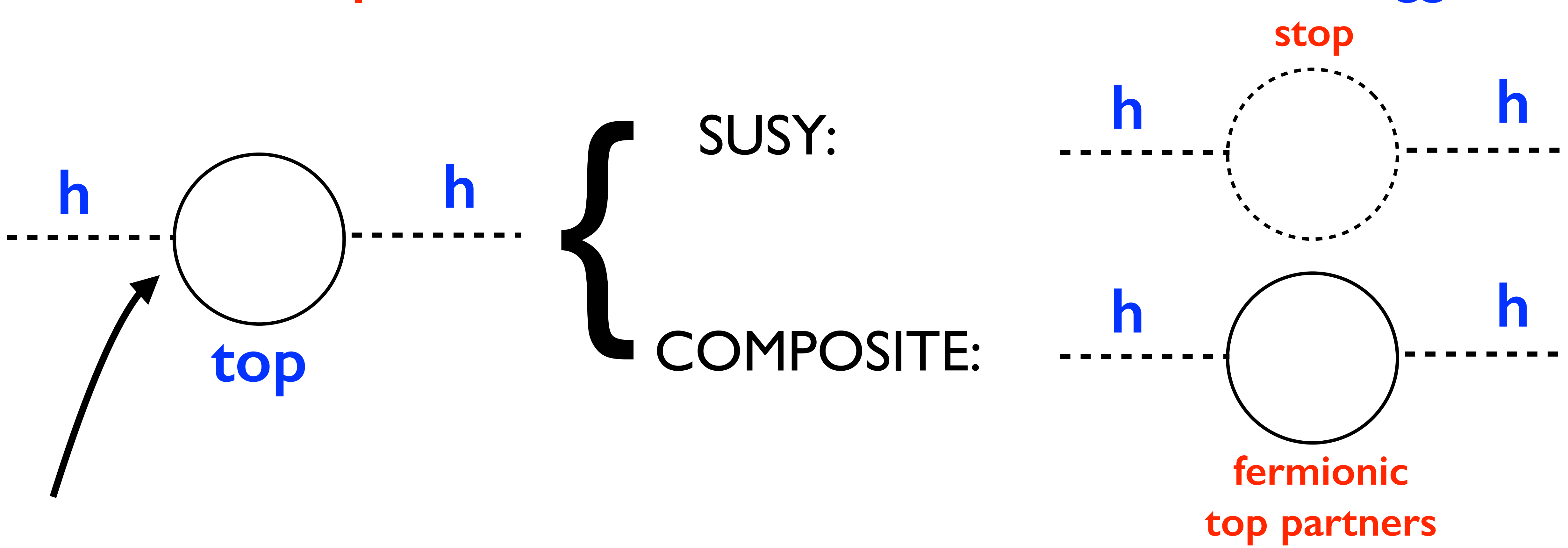


largest Higgs coupling,
largest quantum destabilization

Extra particles to stabilize it

They must be the
lightest if no tunings

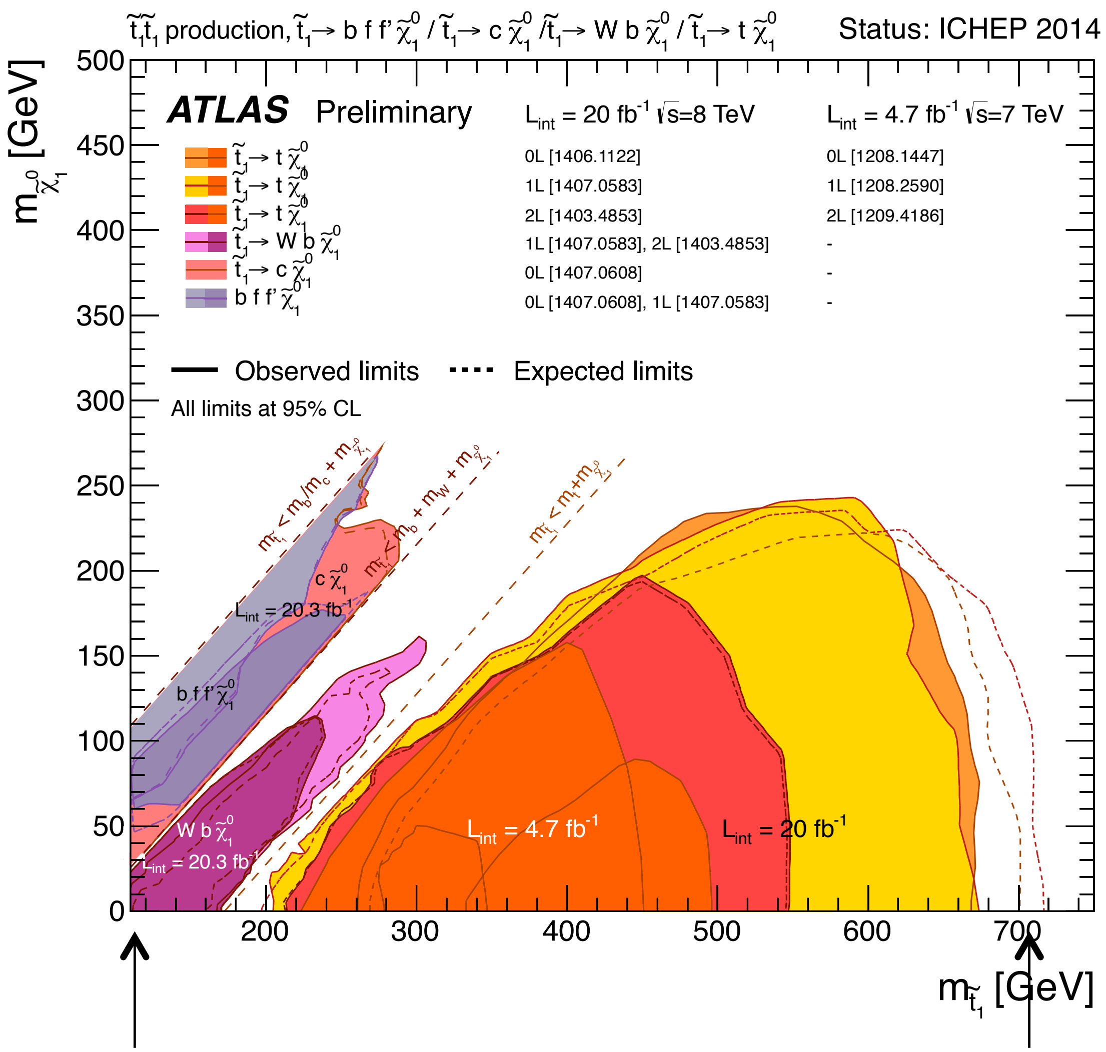
Best chances at the LHC to find new physics:

Stops/Sbottoms:

$$\tilde{t} \to t\tilde{\chi}$$

$$\tilde{t} \to Wb\tilde{\chi}$$

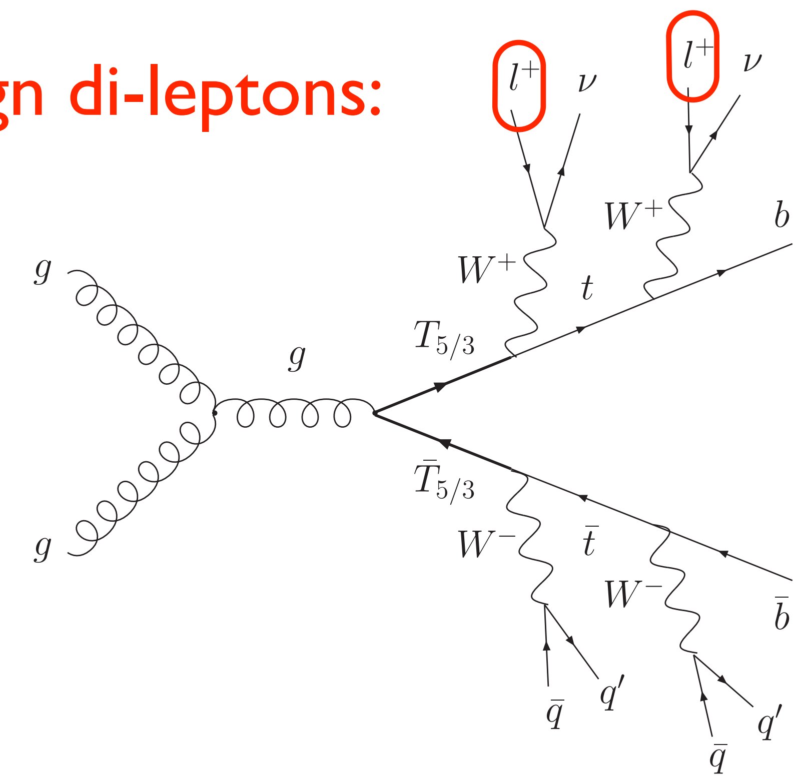
Stable:
missing E_T



100GeV 700GeV

Color vector-like fermions with charge 5/3:

same-sign di-leptons:



ATLAS-CONF-2012-130:

$$M_{T_{5/3}} \gtrsim 700 \text{ GeV}$$

CMS PAS B2G-12-003:

$$M_{T_{5/3}} \gtrsim 645 \text{ GeV}$$

☛ Scratching the interesting regions

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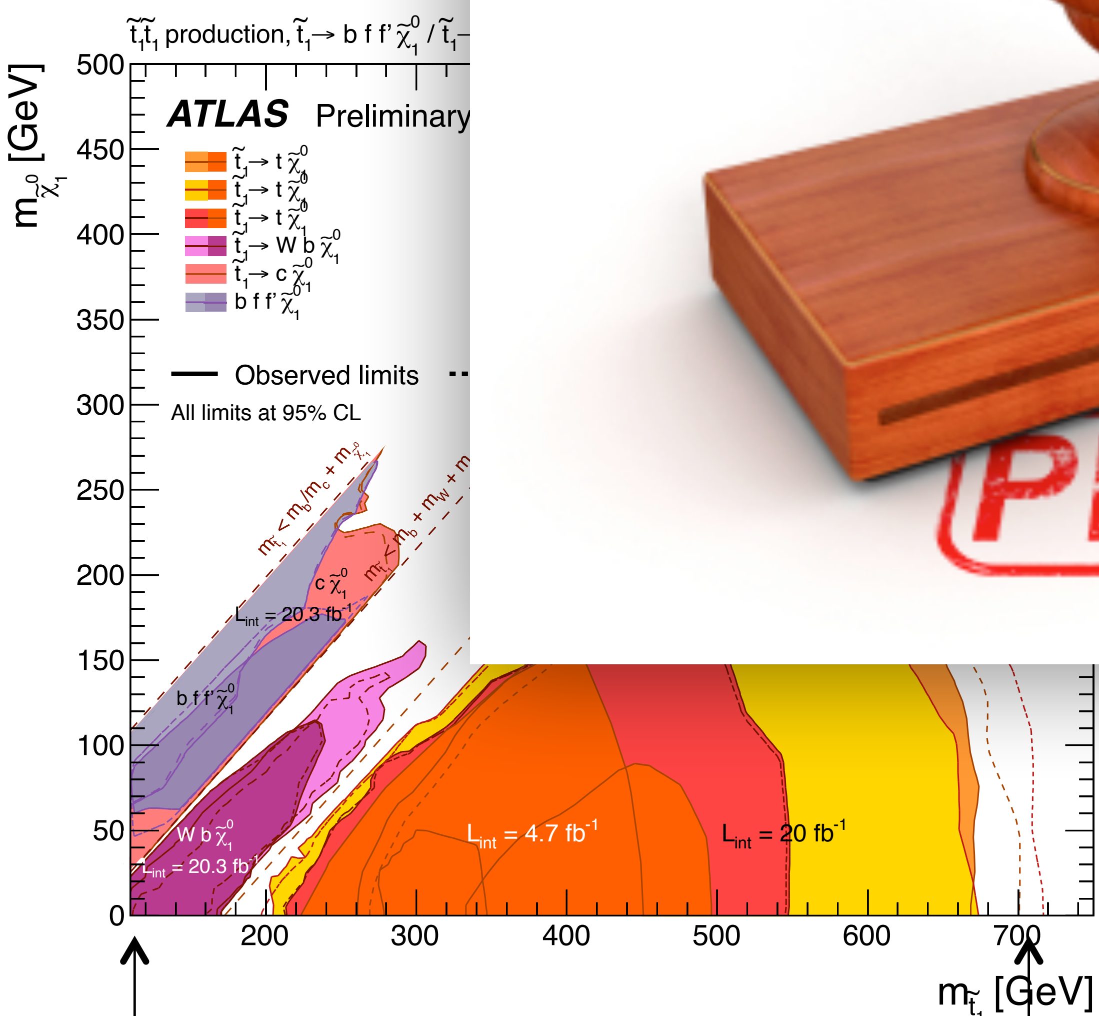

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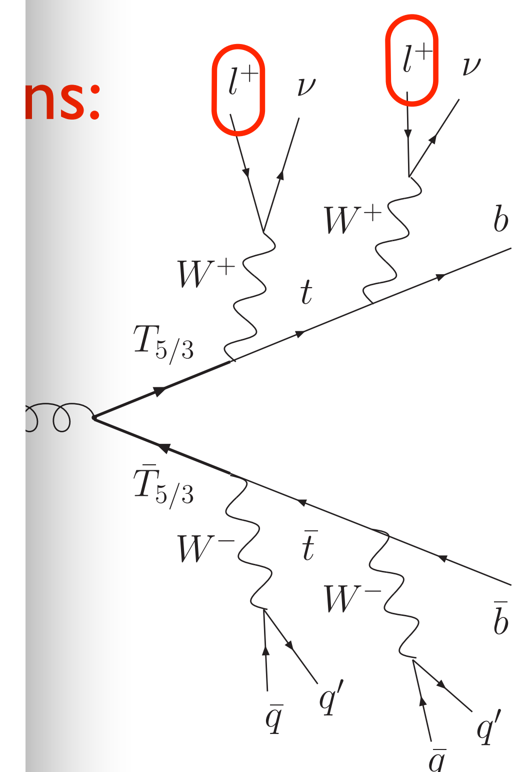

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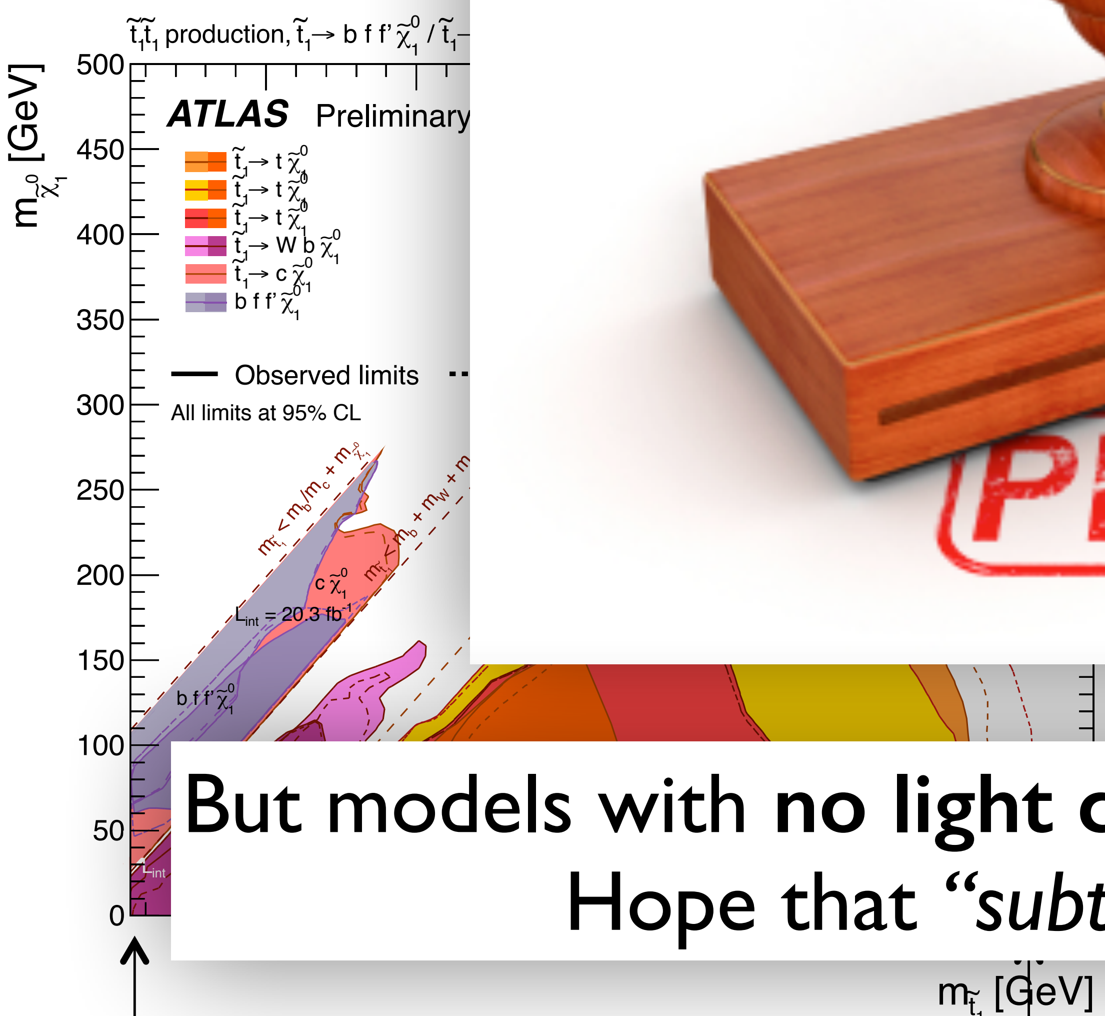

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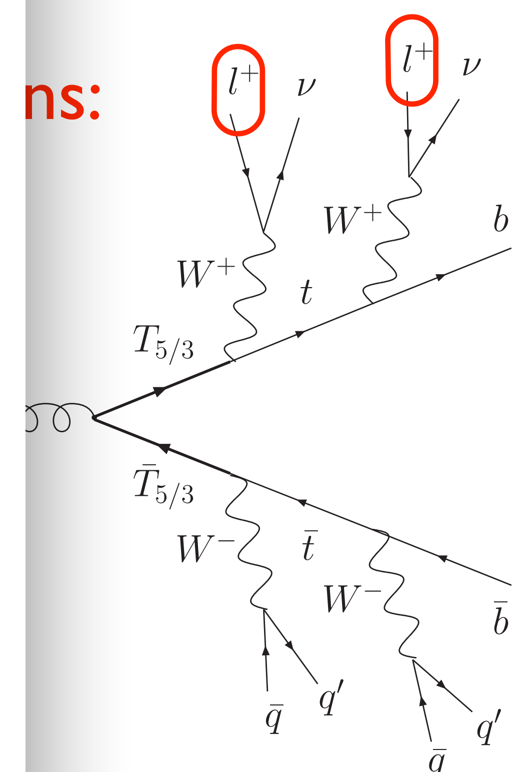


2-130:

$M_{T_{5/3}} \gtrsim 700$ GeV

at the LHC run 2

But models with **no light colored states** are possible (Twin Higgs)

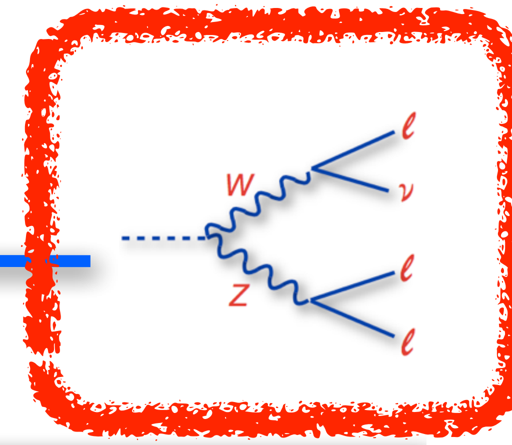
Hope that "*subtle is the Lord, but not malicious*"

☛ Scratching the interesting regions

Lepton-Photon 2015, Borut Paul Kersevan:

ATLAS: arXiv:1506.0096, arXiv:1409.6190,arXiv:1503.04677, CMS: arXiv:1405.1994, arXiv:1405.3447.

Di-Boson Resonances



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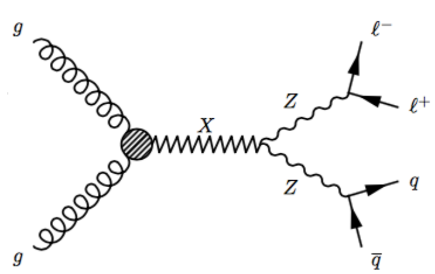
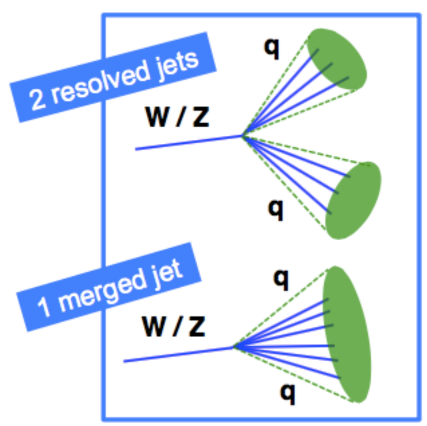
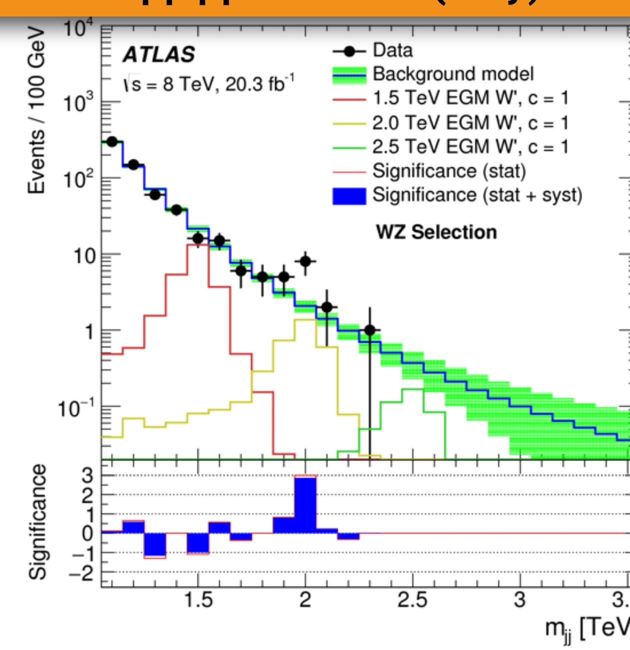
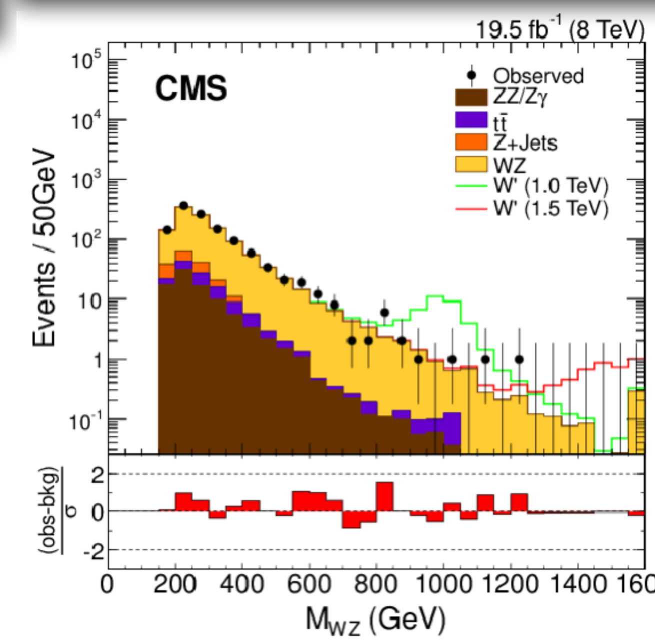
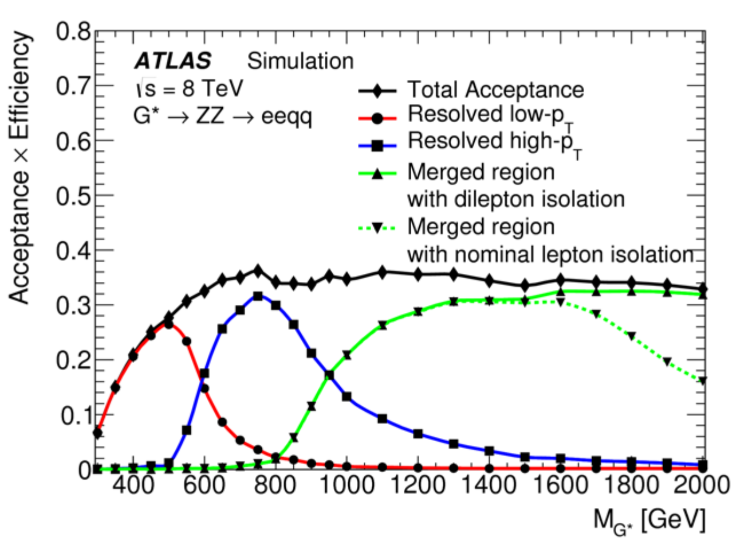
Again, boosted topologies for V→qq at high mass resonances

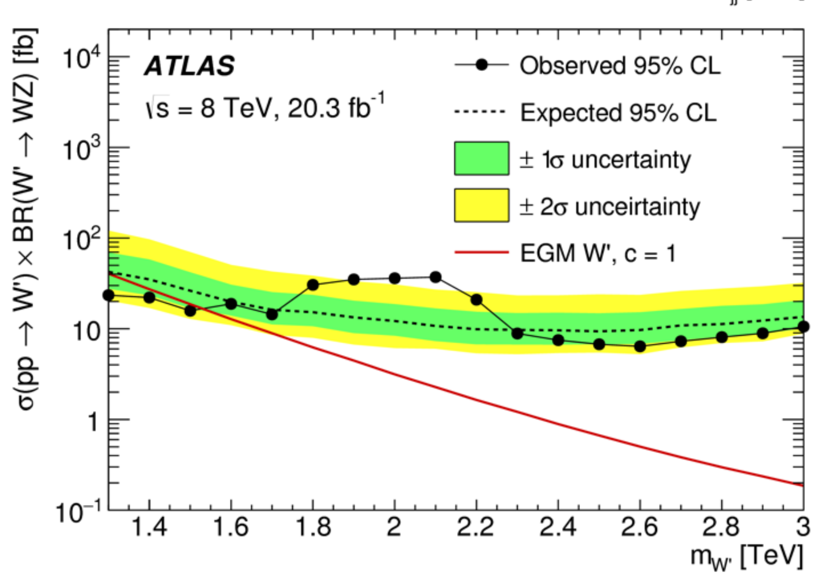


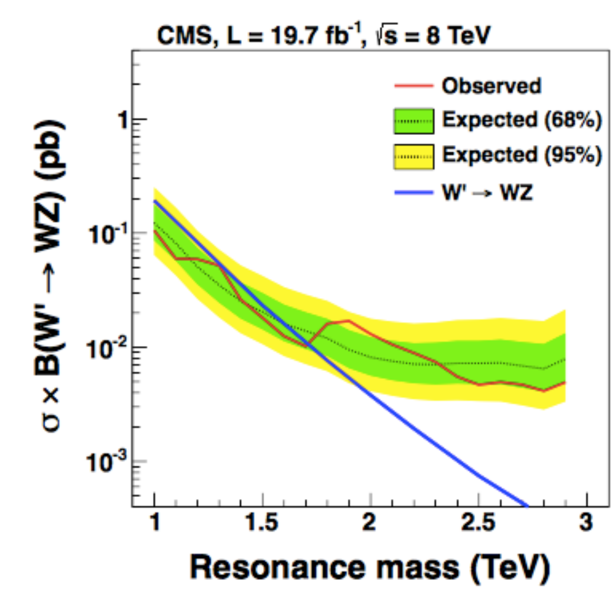












Lepton-Photon 2015, Borut Paul Kersevan:

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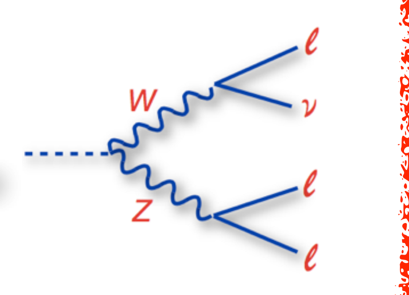
excess?



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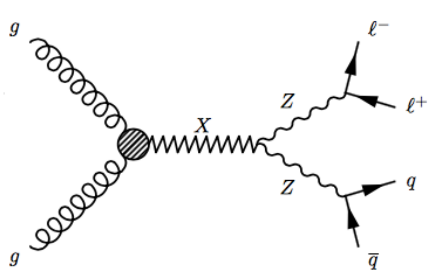

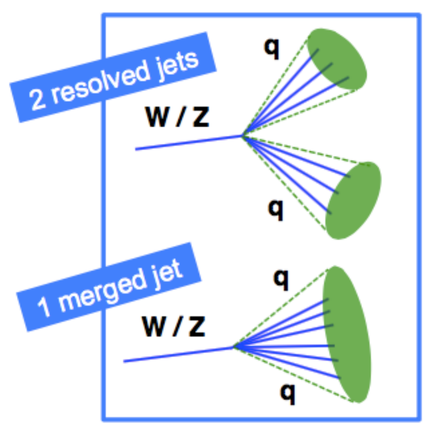

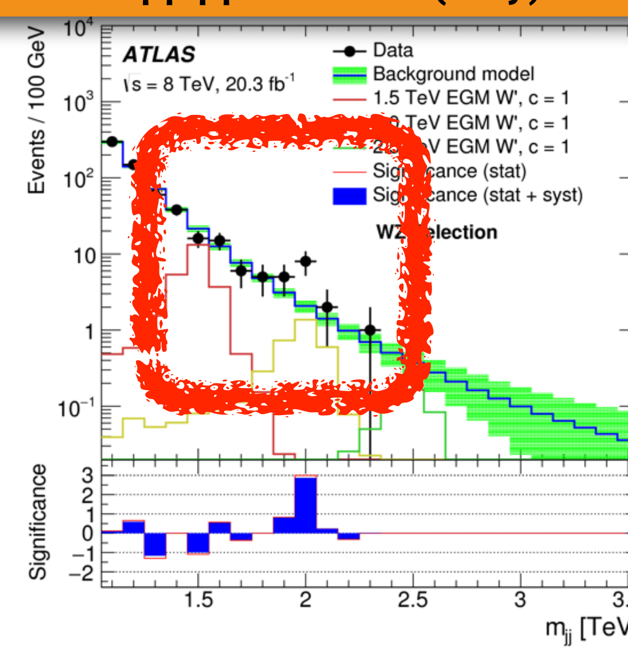

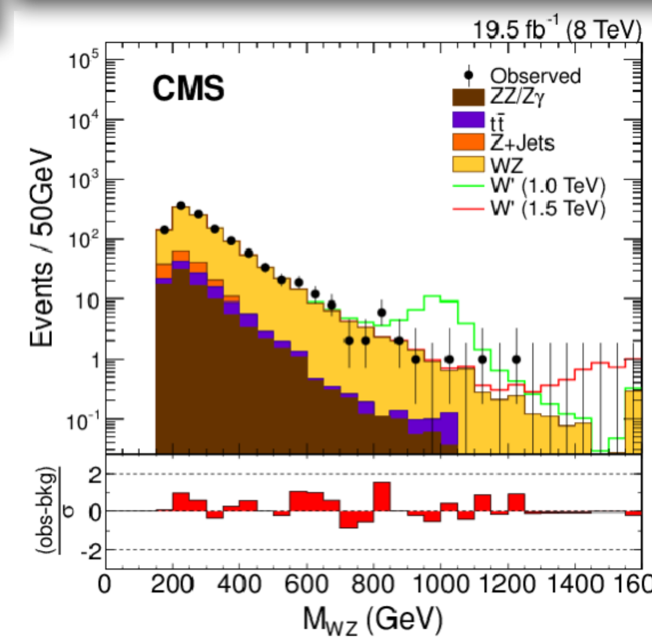

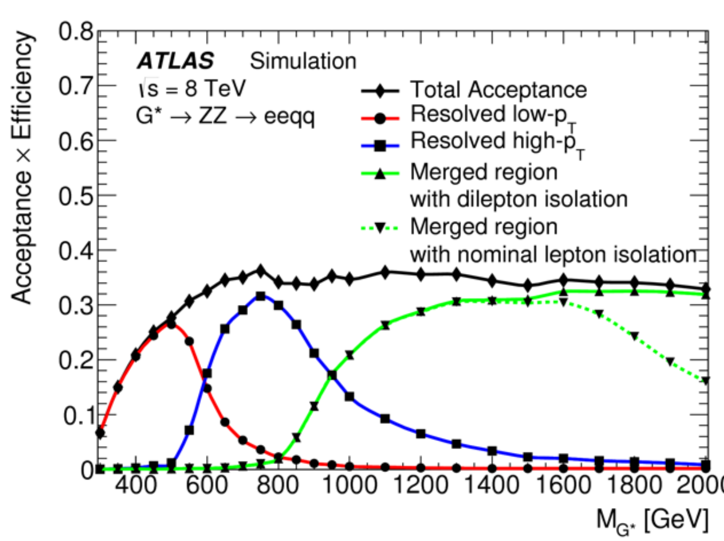

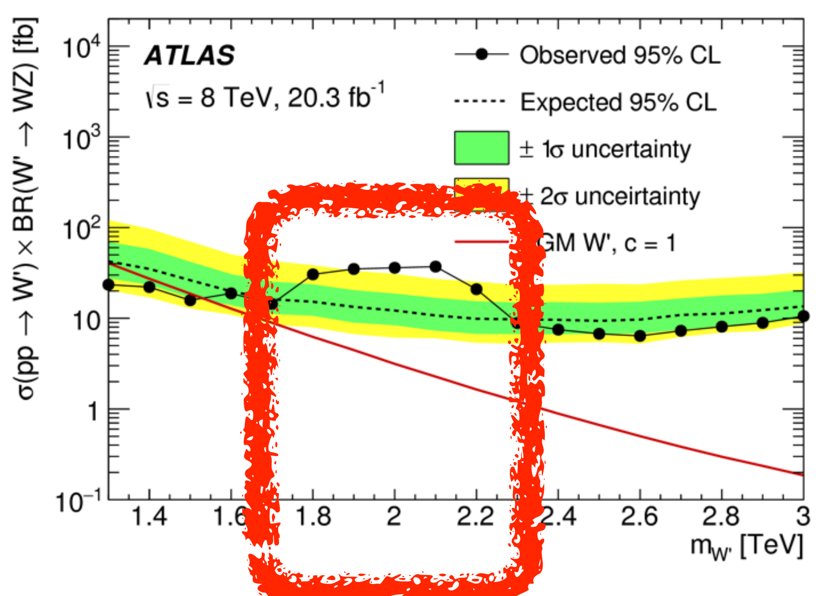

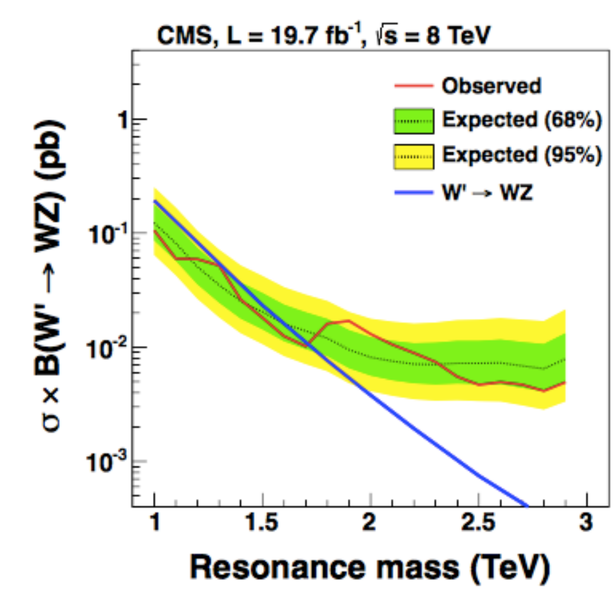

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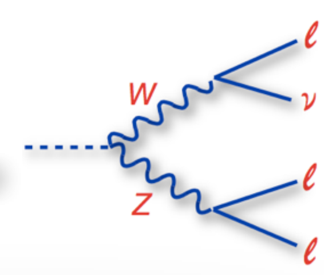

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Expected in composite Higgs (or warped extra-dim) !

Again, boosted topologies for V→qq

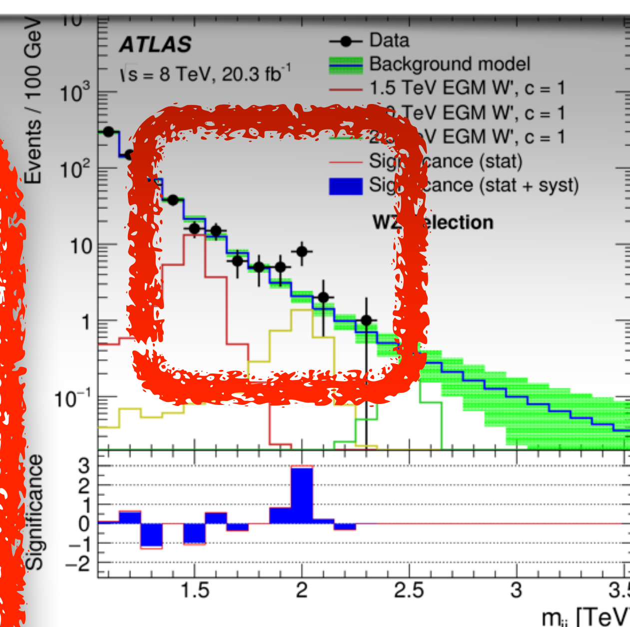
MASS SPECTRUM

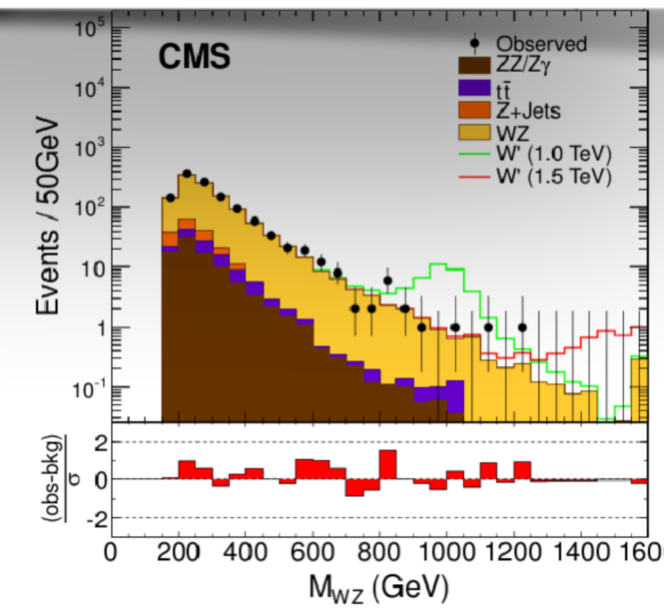
spin=2 resonances

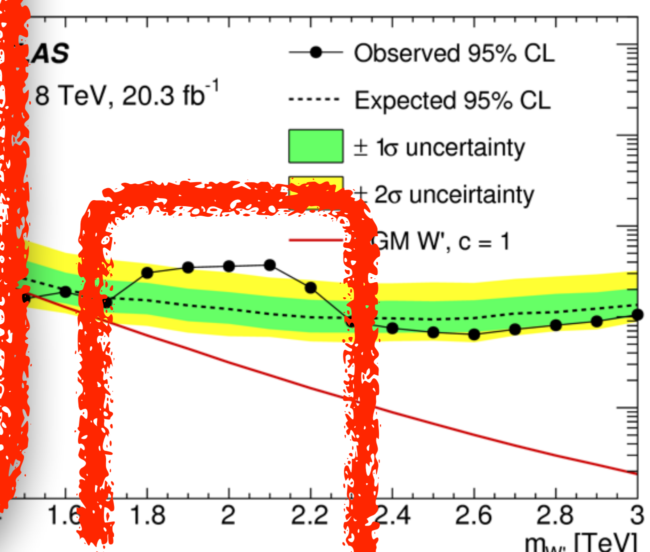
few TeV — spin=1 resonances

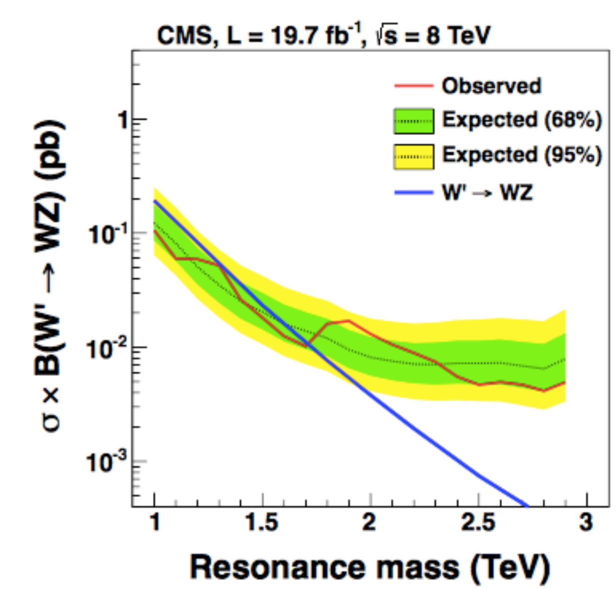
600-1000 GeV — color fermionic resonances

125 GeV — Higgs









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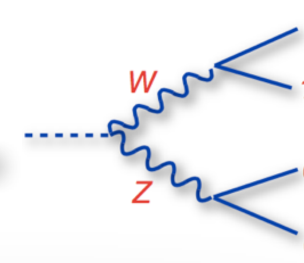

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- spin=2 resonances
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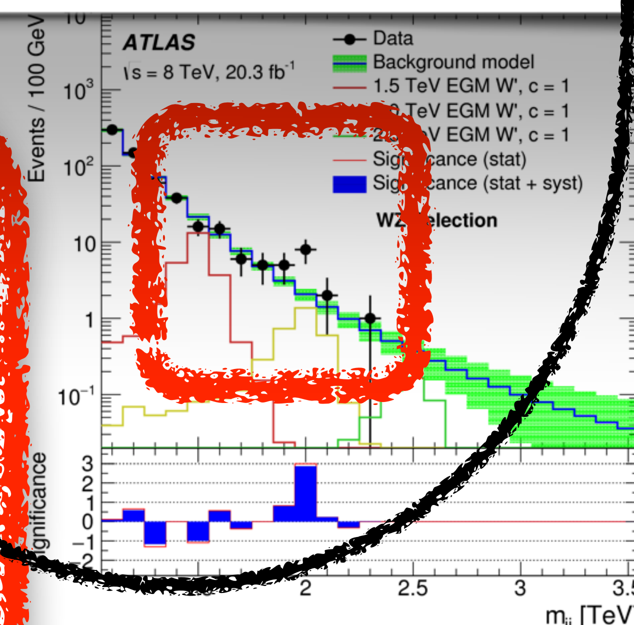

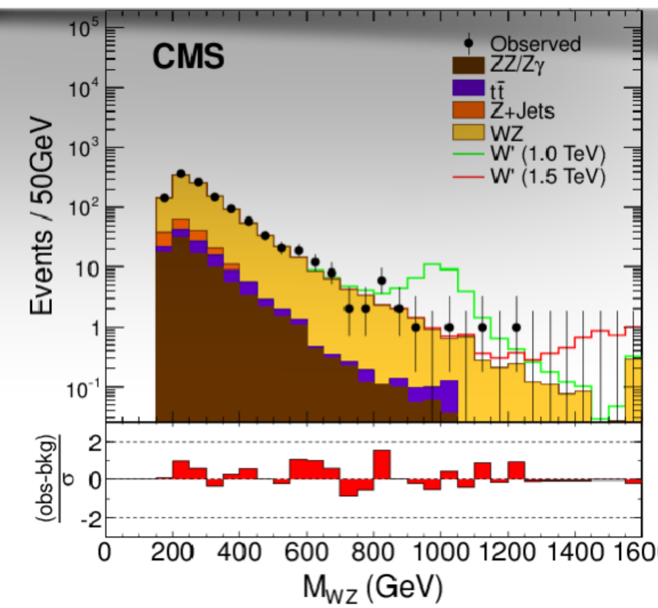

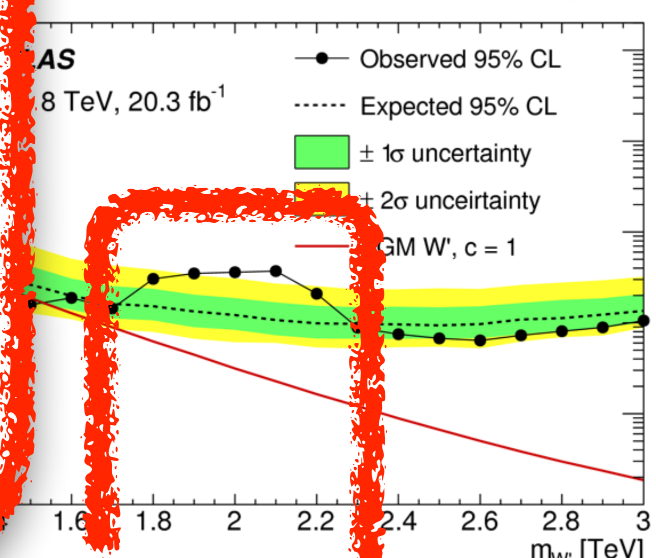

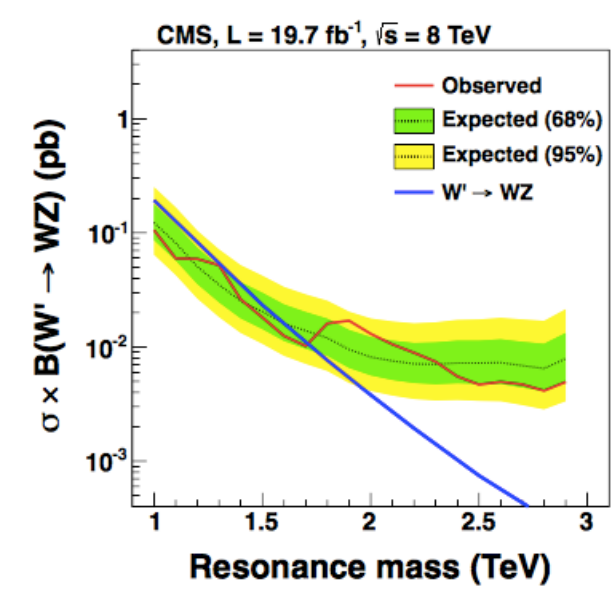

New-Physics at the TeV

Pros

Hierarchy problem

Cons

No new particles seen,
no new flavor-violations seen,
no deviations on Higgs couplings seen,
no deviations on Z/W couplings seen,
no WIMP detected,
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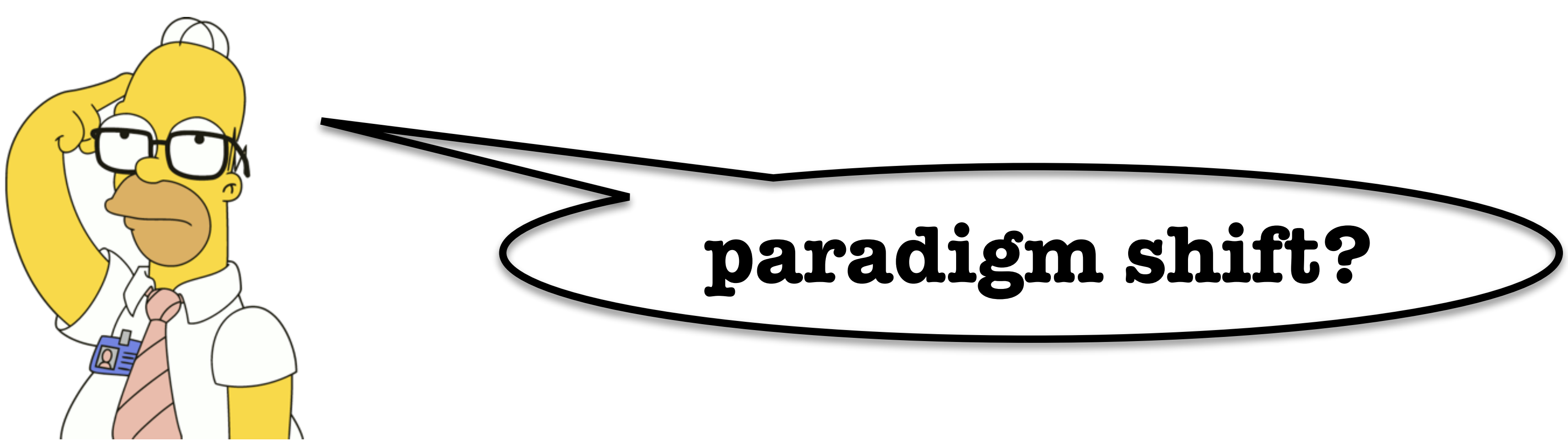

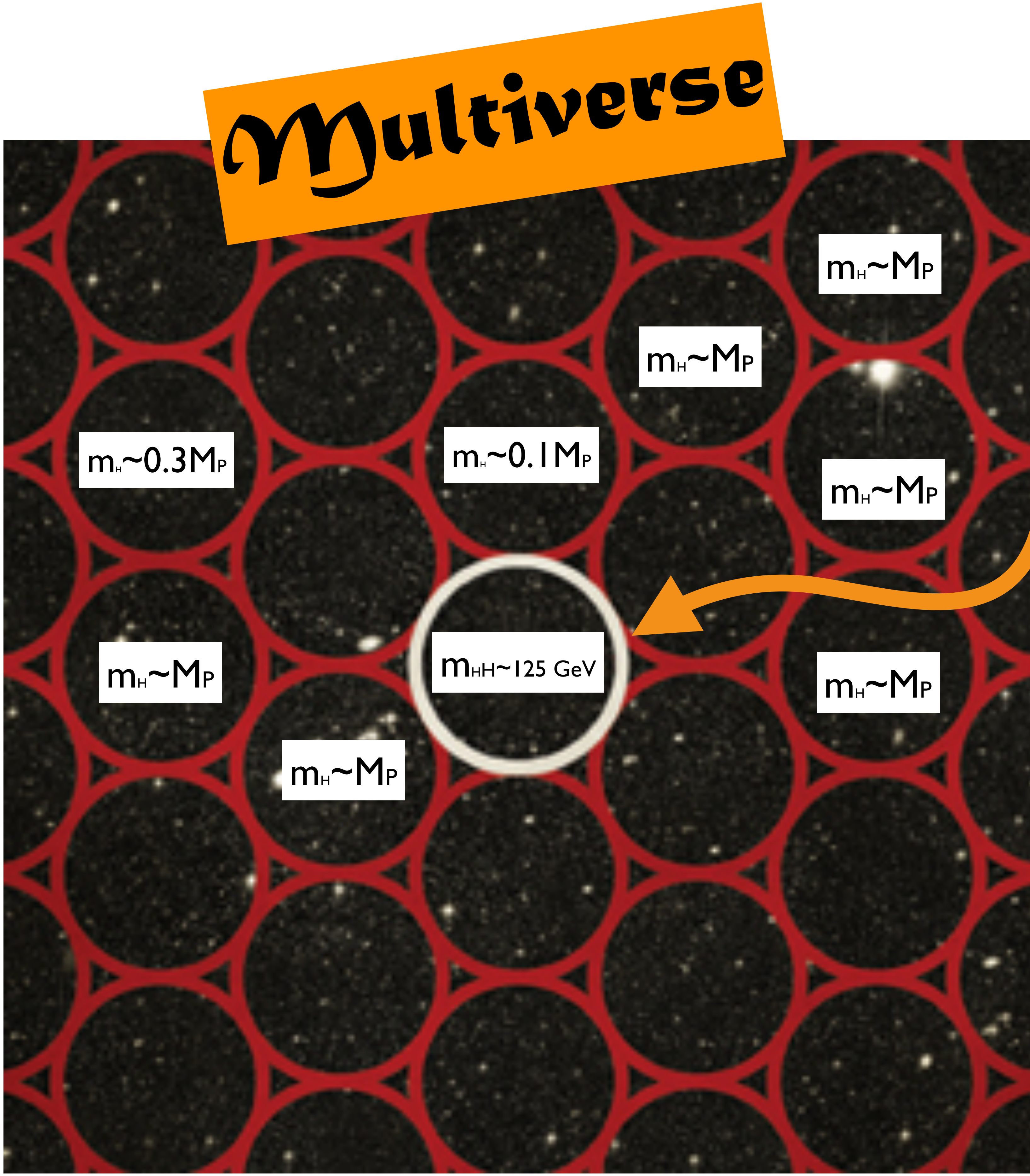

Our **Universe** is very delicate:
Change the SM parameters and could be uninhabitable

"Natural", since only we can "live" in a Universe with these "fine-tuned" parameters

↓

No new physics at the TeV!

(new physics in another universes)

Another new Idea for the Hierarchy Problem:

P.W. Graham, D.E. Kaplan, S.Rajendran
arXiv:1504.07551

"Relaxation" mechanism

(see also earlier work by
Abbott 85,
G.Dvali, A.Vilenkin 04,
G.Dvali 06)

Higgs-mass parameter $\longrightarrow$ Field-dependent Higgs mass

$$m_H^2 |H|^2 \qquad\qquad m_H^2(\phi)|H|^2$$

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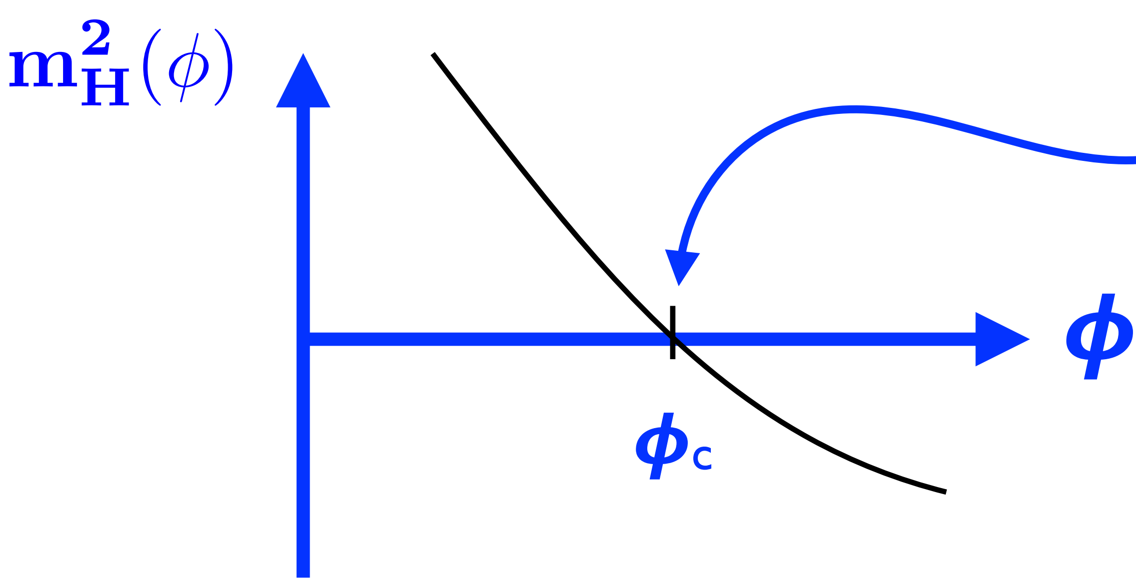
$\boldsymbol{\phi}$ must get a value where $m_H^2(\phi) \ll M_P^2$



it must arise from a “clever”
dynamical interplay
between H and $\boldsymbol{\phi}$

Cosmological evolution can do it for an axion-like ϕ:

$$V(\phi, h) = \Lambda^3 g\phi - \frac{1}{2}\Lambda^2 \left(1 - \frac{g\phi}{\Lambda}\right) h^2 + \epsilon\Lambda_c^4 \left(\frac{h}{\Lambda_c}\right)^n \cos(\phi/f)$$

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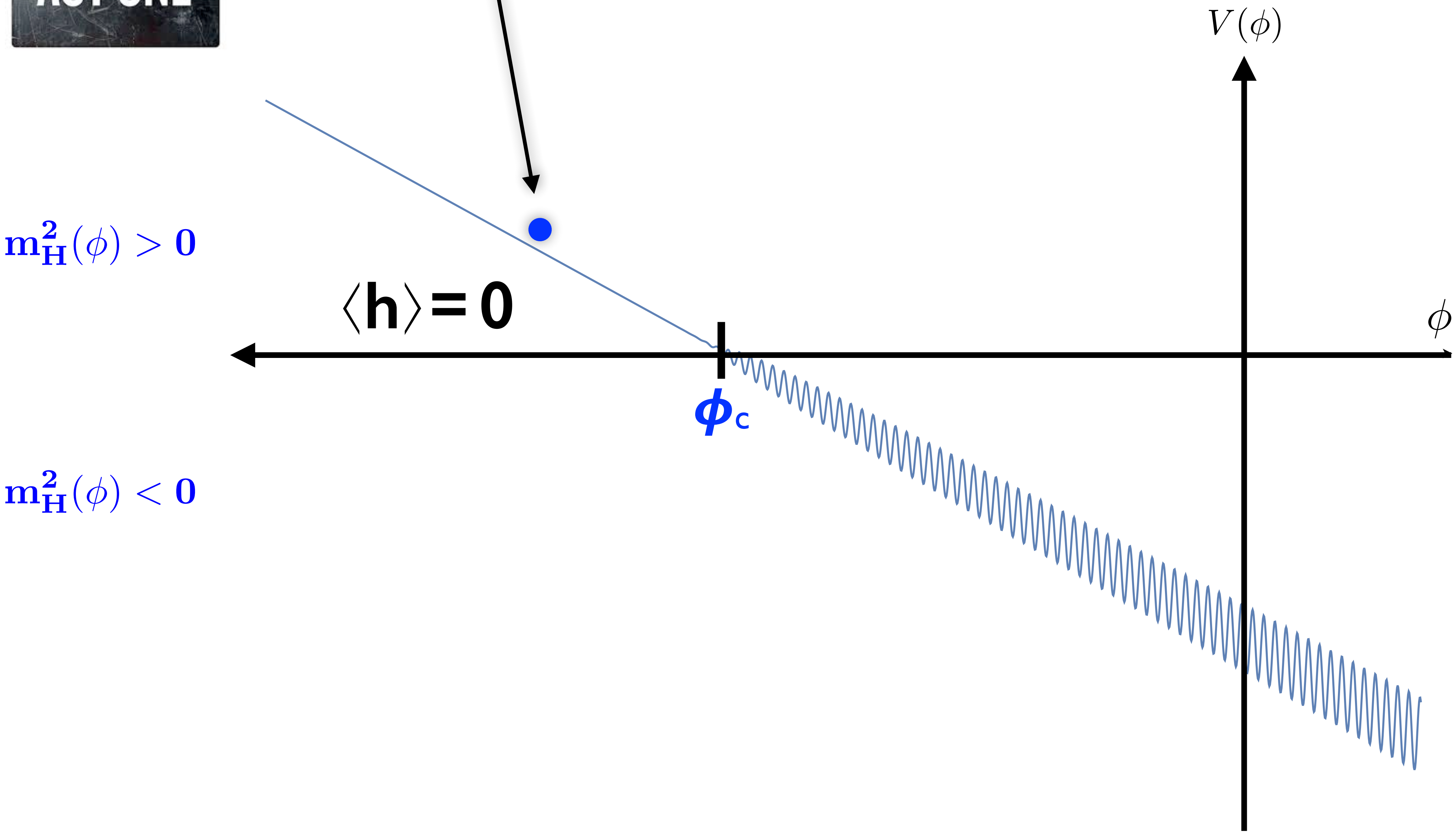

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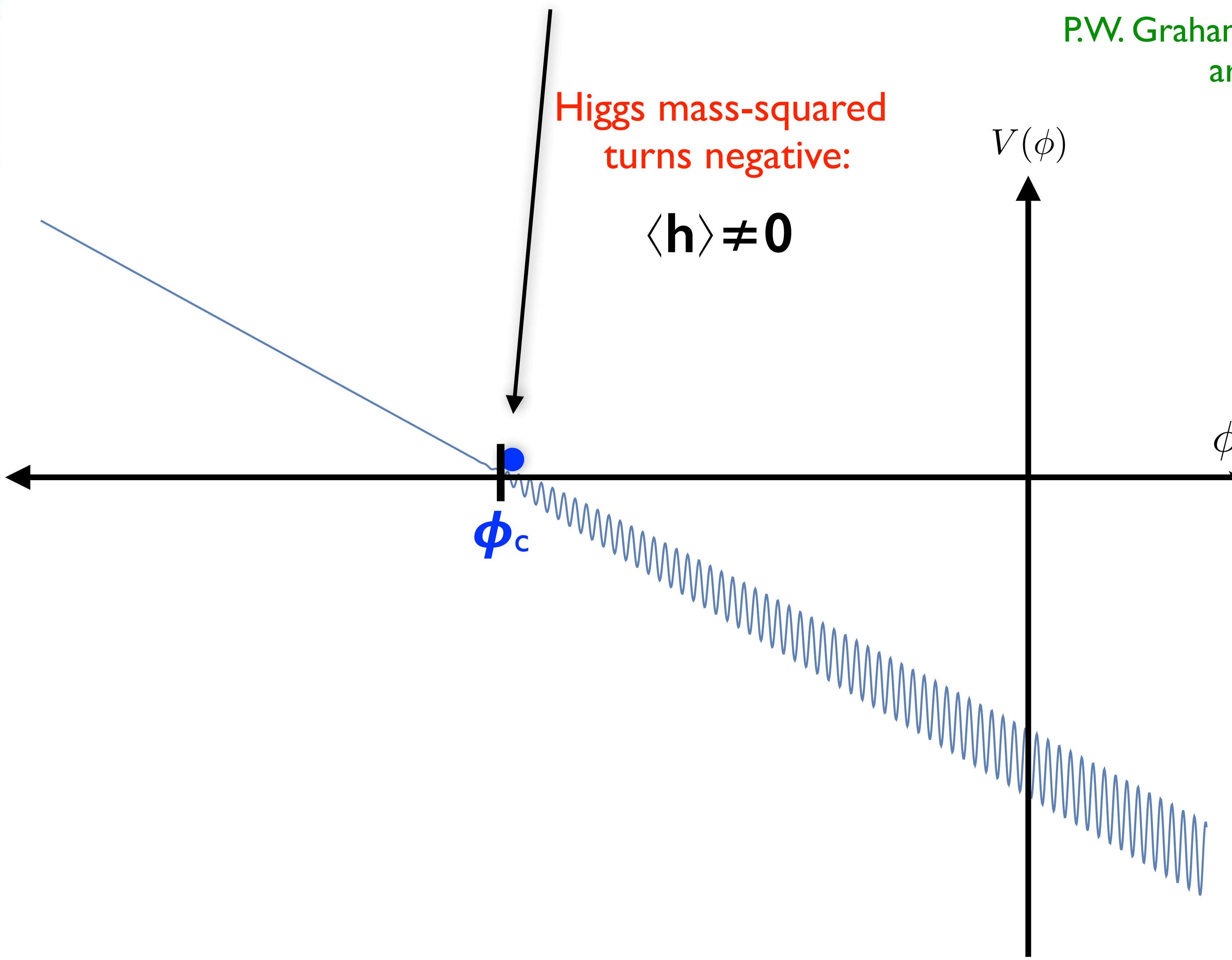

$\mathbf{m_H^2}(\phi) > \mathbf{0}$

$\mathbf{m_H^2}(\phi) < \mathbf{0}$

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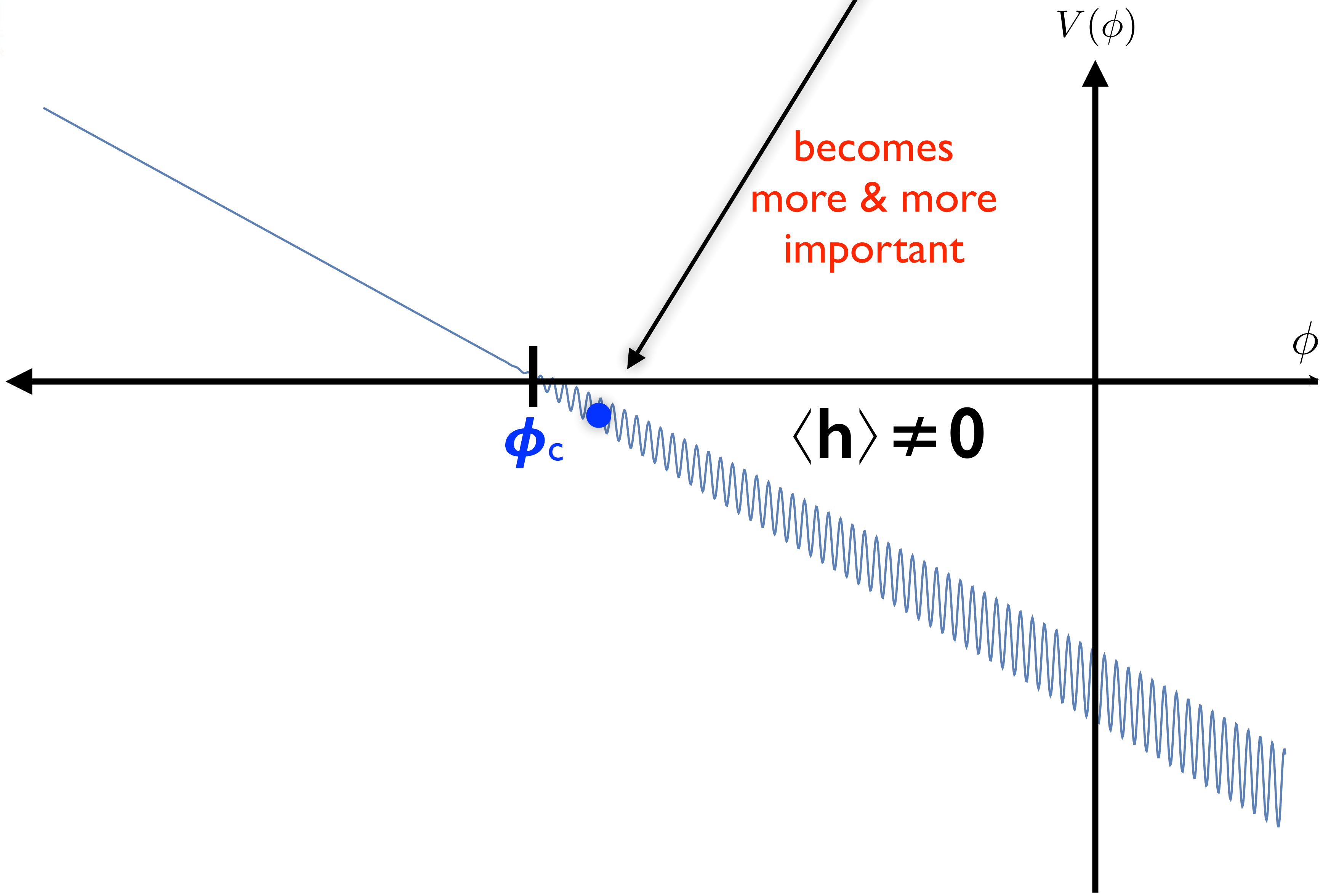

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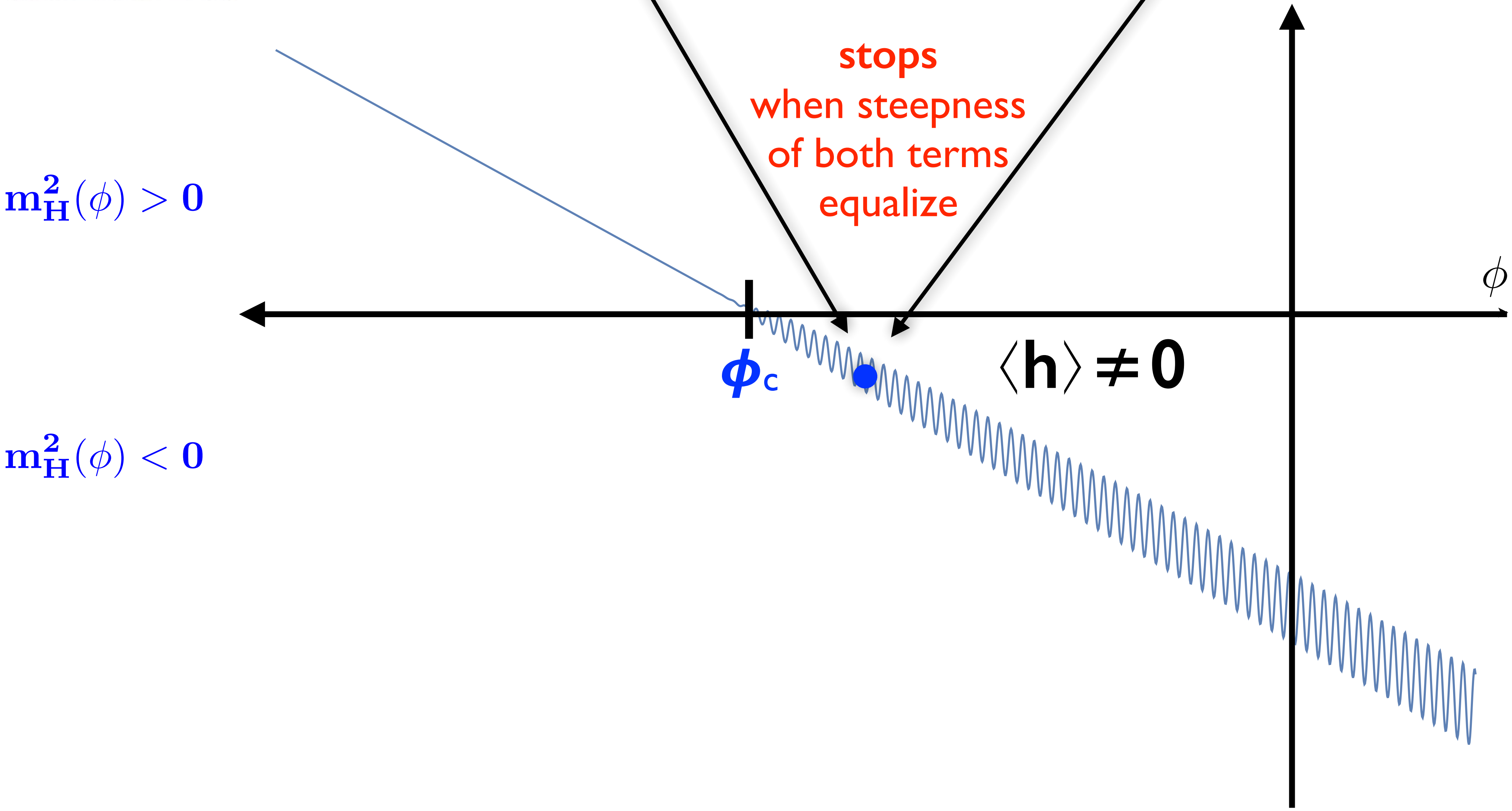

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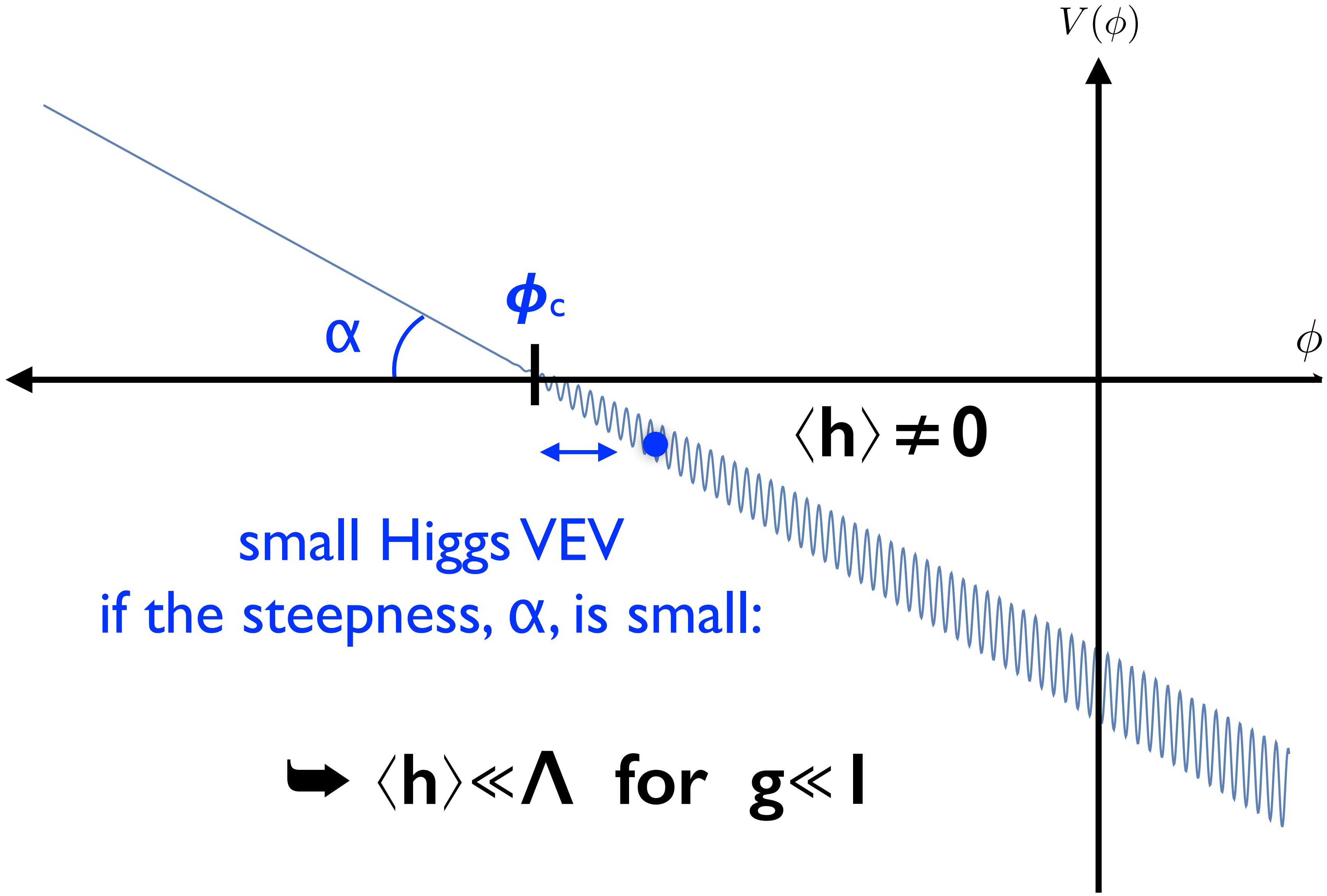

➥ ⟨h⟩≪Λ for g≪1

Higgs (h) & axion-like (ϕ) interplay:

P.W. Graham, D.E. Kaplan, S.Rajendran
arXiv:1504.07551

$$V(\phi,h) = \Lambda^3 g\phi - \frac{1}{2}\Lambda^2\left(1-\frac{g\phi}{\Lambda}\right)h^2 + \epsilon\Lambda_c^4\left(\frac{h}{\Lambda_c}\right)^n \cos(\phi/f)$$

Λ: cutoff of the theory

Λ_c : scale that originates the periodic term

Spurions:

g $\ll 1$: breaking shift symmetry $\phi \to \phi + c$

ϵ $\ll 1$: breaking of shift symmetry, respecting $\phi \to \phi + 2\pi f$, $\phi \to -\phi$

<u>potential stable under radiative corrections!</u>

Tuning the initial conditions?

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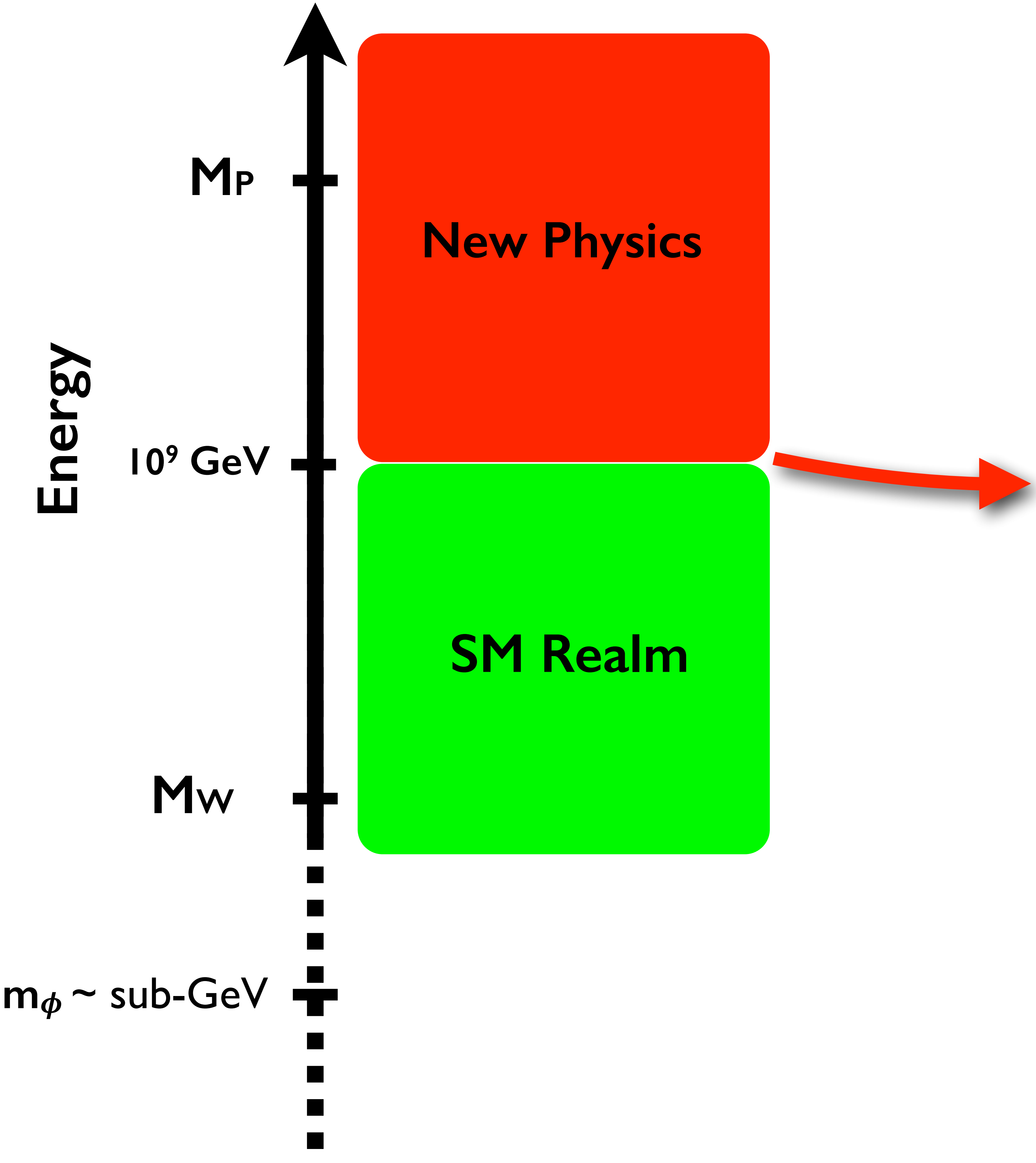
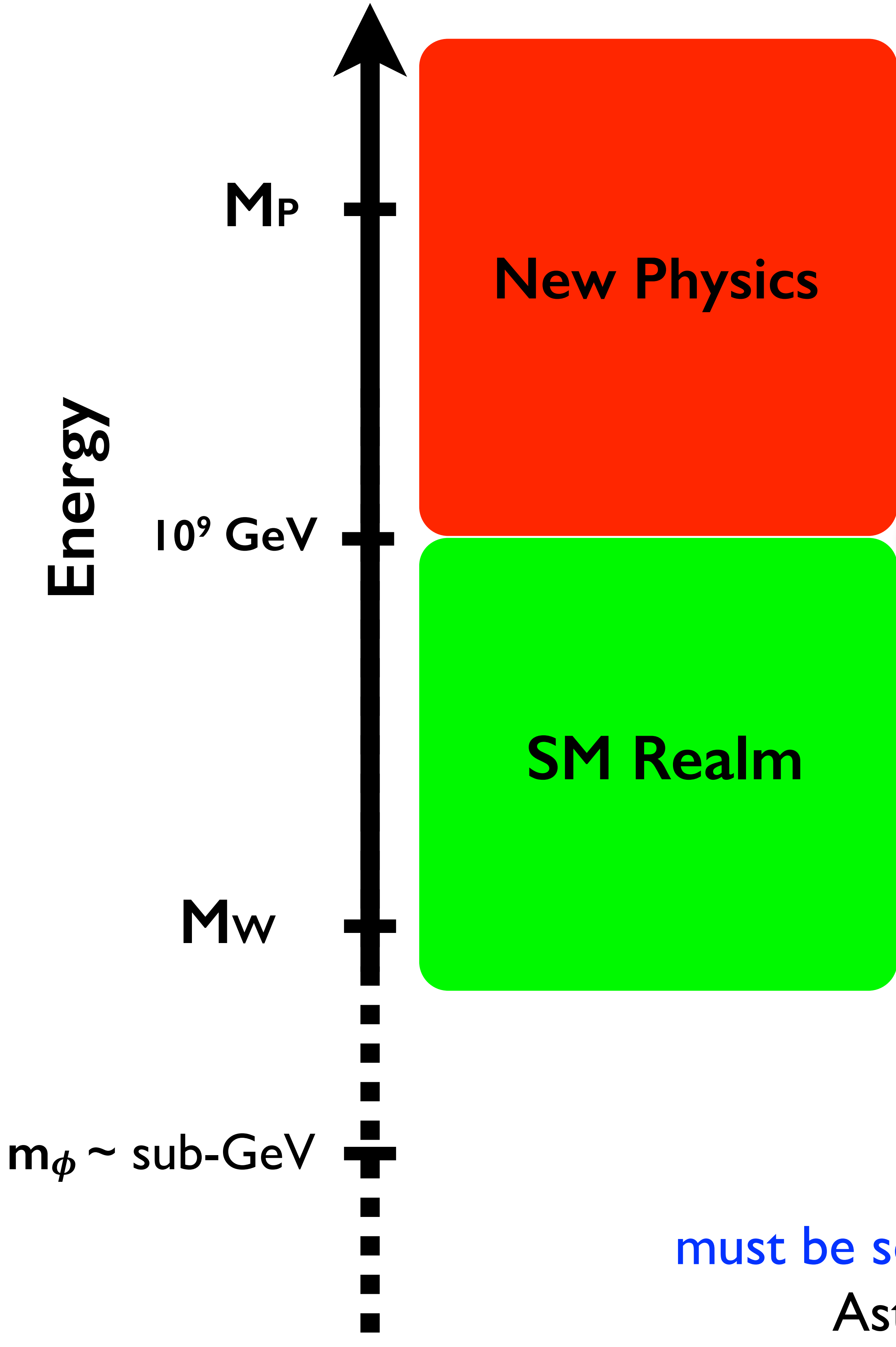
Long period of inflation needed,
in order for $\boldsymbol{\phi}$ to "scan" large ranges of the Higgs mass

e-folds needed: $N_e \gtrsim \dfrac{H_I^2}{g^2\Lambda^2} \sim 10^{40}$



New physics scale can be pushed up naturally to at least 10^9 GeV

see for example,
J.R.Espinosa,C.Grojean,G.Panico,A.P.,
O.Pujolàs,G.Servant 15



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Main prediction:

ϕ's: very light & extremely weakly-coupled states (*axion-like*)

must be searched in different type of experiments:

Astro (γ-rays, pulsar timing, …), CMB,
table-top (fifth-force searches, EPV), …

Conclusions

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  ➥ **No need** for anything else
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  Either supersymmetry, new strong-dynamics or something else

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Epilogue: Don't be afraid of null results: As Michelson-Morley experiment, also null results (from well-motivated experiments) can lead to a change of paradigm